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Vision and the Lighting Requirements of Ducks (*Anas platyrhynchos domesticus*) and Turkeys (*Meleagris gallopavo gallopavo*)

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Abstract

In poultry housing where the light environment is provided artificially, it is largely designed to meet the requirements of human vision and poultry production and does not necessarily consider the bird's visual abilities. Extrapolation of research from fowl to other poultry species may be inappropriate, given their different ecological backgrounds. The overall aim of this thesis was to investigate vision in domestic ducks and turkeys and their light requirements.

The spectral sensitivity of domestic ducks, domestic turkeys and humans was investigated using a behavioural test. Ducks and turkeys had similar spectral sensitivities, extending into the UV_A part of the spectrum, with a broader range than humans. These results imply that the lux unit is inappropriate for describing the illuminance of a light source, as perceived by ducks and turkeys.

The light environment in commercial duck and turkey housing was surveyed: mean illuminance was 22.6 and 5.3 lux, respectively. The spectral power distributions of the light sources and the birds' spectral sensitivity were used to estimate illuminance as perceived by ducks and turkeys; this varied by up to ~20% depending on light source.

In a preference test ducklings and turkey poults were given a free choice between illuminances of <1, 6, 20 and 200 lux at two and six weeks of age. Ducklings spent least time in <1 lux though this was not affected by age. Turkey poults showed an overall preference for 200 lux at two weeks and ≥20 lux at six weeks. For both species, illuminance significantly affected the partition of behaviours.

These results show that domestic ducks and turkeys have good colour vision, including UV_A perception, and have distinct illuminance preferences. They imply that full spectrum lighting of varying temporal or spatial illuminance in housing might benefit welfare and satisfy preferences. Future work is needed to assess the use of UV_A radiation by poultry and the strength of their motivation for illuminance.

To Linda, Vic, Ruth and Tom

"The study of colour vision in animals other than man is, at best, a troublesome and uncertain occupation."

F. Crescitelli & J. D. Pollock (1972)

How birds see the world

G. Larson (1984). The Far Side®. FarWorks, Inc.

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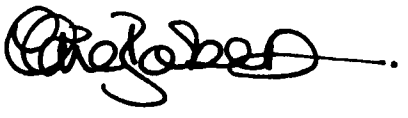
Author's Declaration

I declare that the work in this dissertation was carried out in accordance with the Regulations of the University of Bristol. The work is original except where indicated by special reference in the text and no part of the dissertation has been submitted for any other degree. Any views expressed in the dissertation are those of the author and in no way represent those of the University of Bristol. The dissertation has not been presented to any other University for examination either in the United Kingdom or overseas.

SIGNED:  DATE: 31st October 2003

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General Introduction

Today, poultry producers are showing greater interest in the development of production systems that are not only economically viable, but also satisfy as far as possible the behavioural needs of the birds. Given the great influence of environmental factors on the behaviour, health and welfare of poultry, increasing attention is being paid to aspects of environmental control within poultry housing, including lighting, stocking density, aerial pollutants and litter management. One of these factors which has a particular biological relevance for poultry is lighting. At present the design of lighting systems in poultry housing is largely determined by production parameters, ease of maintenance and human vision, with limited regard given to the visual abilities of the birds. Whilst we now have a good understanding of the effects of lighting, especially intensity and duration (photoperiod), on reproduction and productivity, relatively little is known about the visual abilities of poultry or their involvement in key behaviours, such as social interactions and feeding, particularly for ducks and turkeys.

It is widely acknowledged that poultry are highly visual animals, and that vision is of great importance in the control of their behaviour, as shown by their well-developed visual sensory system. Knowledge of how the sense of vision functions in poultry is therefore important to aid the understanding of their behavioural mechanisms, and their behavioural needs for light. The structure of the domestic poultry visual system is an evolutionary legacy from their wild progenitor species; and presumably evolved to function in the range of light conditions that are found to prevail in their natural habitats. Variations in the optical structure of avian eyes may be accounted for in terms of general ecology and behaviour (Martin, 1999), making it important to consider the natural habitats and origins of domestic species when investigating their visual ecology in modern poultry housing. Subtle differences in the structure of the eye, and the rest of the visual system, will have consequences for how different poultry species perceive their environment.

The effects of lighting on the production, behaviour, health and welfare of poultry are mediated mainly by vision. How poultry visually perceive their external environment will influence how they interact with the environmental conditions under which they are reared within commercial housing. This makes light control an important management tool for producers. The manipulation of lighting can have profound effects upon both

behaviour and physiology (Manser, 1996). How this may affect the productivity, health and welfare of housed poultry, and in particular ducks and turkeys, is reviewed in the latter sections of chapter two.

In the late 1960's concern was expressed about the lack of research carried out on turkey production (Coleman and Leighton, 1969). The industry at the time based many of its practices on work done with domestic fowl or the opinions and experiences of growers. Whilst domestic fowl and turkeys are often considered biologically similar, there are differences regarding their biology and production. Indeed, the chromosomes of the turkey were reported to be more similar to those of the pheasant than to those of the domestic fowl (Sokolow et al, 1936; cited by Schorger, 1966). However, developments in molecular genetics now use comparisons of DNA sequences to quantify genetic divergence between species more accurately. This, and related technologies, are currently employed within international genome projects to map and compare the genomes of poultry and other farmed species (ARK-Genomics, 2003). Therefore, production systems are becoming more species-specific and the environmental conditions which these birds are now reared in vary in some key management aspects such as temperature and lighting. More recently, the same concerns that were initially raised about turkeys regarding the lack of research and the application of information based on extrapolation from other poultry species are being expressed with regard to the domestic duck. There now exists a wealth of literature on domestic turkeys regarding their production and the influence of light. Similar information regarding the domestic duck is scarce, although several studies that investigate the ecology of wild ducks highlight the role of vision in behaviours such as foraging, predator detection and mating. The following review concentrates where possible on species-specific literature, although studies of other poultry and avian species are cited where appropriate.

Currently, too little information exists on which to base guidelines or recommendations for the light environment of duck and turkey housing that satisfies both welfare and economic concerns. If we require that poultry are housed in intensive housing with artificial lighting for production reasons, then further experimental research is needed. This includes assessment of the visual abilities of poultry species that are pertinent to lighting issues, from which hypotheses can be posed as to how various lighting parameters may influence the behaviour and welfare of the birds. Calls for further

research into the preferences and motivation of poultry for various aspects of lighting and the requirements for light for different activities have been made to determine the optimum lighting conditions (FAWC, 1995; Manser, 1996).

Another area of lighting research for poultry which requires review is the manner in which the light environment in poultry housing in described and measured. In past research, the light environments or treatments used in numerous experiments have often been only partially or inaccurately described with regard to the four aspects of lighting which may influence the physiology and behaviour of poultry: source, duration (or photoperiod), wavelength (or colour) and intensity (from now on referred to as illuminance). There is a requirement for accurate description and measurement of the light environment as experienced by poultry, both commercially and experimentally, with the use of calibrated equipment and trained personnel (Prescott et al, 2003).

In the following two chapters a review of literature is made to illustrate the current knowledge of the domestic duck and turkey origins, visual biology and ecology, and the influence of these and lighting on recent husbandry practices. Chapter one provides background information on the origins, domestication and present status of duck and turkey production, to highlight the different ecological backgrounds of these birds and put into context the social and economic importance of research on these species. In the first part of chapter two, a review of literature discusses the importance of vision for these birds, their eye structure and visual ecology, to highlight the current understanding of the properties of the visual system, visual capabilities and visual ecologies of these birds. This is of particular importance if we are to investigate how they perceive and interact with the light environment under which they are reared commercially. Literature concerning the effects of light wavelength and illuminance on poultry production, health and behaviour is also reviewed in chapter two, along with the current recommendations and guidelines for ducks and turkeys regarding lighting. The remaining chapters of this thesis details the experimental studies that were carried out in the course of this project, and a discussion of the results, implications and conclusions drawn from this work.

The overall aim of the experimental work was to investigate various aspects of illuminance, as perceived by domestic ducks and turkeys, of commercially used light sources in duck and turkey housing. As light wavelength and illuminance interact to influence the visual perception of illuminance from a given light source, it was

necessary to investigate the perceived spectral sensitivity of domestic ducks and turkeys. Any differences between these birds in their spectral sensitivity will have implications for how illuminance is perceived and measured for such birds. A survey of the light environment in poultry houses, particularly in relation to wavelength and illuminance was undertaken, and data from this and the spectral sensitivity work were used to estimate the perceived illuminances of a range of light sources used commercially, for domestic ducks and turkeys (see below). The preferences of growing ducklings and turkey poults for different illuminance levels in relation to their age and behaviour were also investigated to gain a better understanding of the behavioural requirements of these birds for illuminance. Whilst it is acknowledged that the duration of light has significant effects on poultry productivity, physiology and behaviour (for a review see Manser, 1996), this aspect of lighting was not investigated in detail in this thesis.

Throughout this thesis the photometric quantity of illuminance will be used to describe the "brightness" of a light source perceived by either a human or animal. However, it should be noted that the correct definition of illuminance refers to the amount of light falling on a surface per unit area, as measured in the lux unit (lm/m^2). The lux is a photometric unit which is calculated from the spectral power distribution of a light source and the spectral sensitivity of the human (Prescott et al, 2003). Therefore, the term illuminance is only accurately used when referring to quantities of light measured in lux to describe human "brightness" perception. Unfortunately, there is not an equivalent photometric quantity to describe the same quantity of light when perceived by a non-human animal. Thus, the term illuminance has been used in this thesis with reference to that perceived by poultry as well as humans. Additionally, the calculation or estimation of "perceived illuminance" for fowl, ducks and turkeys in this thesis refers to the illuminance perceived by these birds after correction for the birds' spectral sensitivity. These "perceived illuminances" have units that are specific to the species concerned e.g. like the *c*lux (Prescott and Wathes, 1999a) and galluminance (Nuboer et al, 1992) units for domestic fowl. In the literature the perceived illuminances calculated for domestic fowl have also been referred to as alternative units or correction factors to the lux for measuring fowl-perceived illuminance (Prescott and Wathes, 1999a; 2003). These terms are only used in this thesis when referring to the units calculated by these researchers, as they inaccurately imply the units of poultry perceived illuminance are of the same standing as the lux unit, which is a standard international unit.

Chapter 1:

The Origins, Domestication and Present Status of Domestic Duck and Turkey Production

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1.1 Introduction

Over the past 50 years, poultry production has undergone major intensification that has revolutionised the way poultry are reared and produced. The recent history and current status of commercial duck and turkey production are discussed below, detailing briefly some of the profound changes in production methods that have shaped the development of present domestic strains of domestic ducks and turkeys. This background information is included in this chapter to put into an economic context the importance of research investigating the production, behaviour and welfare of ducks and turkeys, and how these may be influenced by vision and lighting.

Prior to a review of literature discussing vision and the impact of lighting on poultry, and in particular, domestic ducks and turkeys (see Chapter 2), it is important to give some consideration to the origin, natural habitat and domestication of the progenitors of the modern, commercially reared birds. These progenitor species would presumably have evolved to adapt to the range of conditions found in their natural environments, resulting in characteristics in their physiology and ecology that has made them suitable candidates for domestication. Over the past 4000 years a number of poultry species from the orders Anseriformes and Galliformes have been domesticated. Of these the domestic fowl (*Gallus gallus domesticus*) is undoubtedly of greatest economic importance world wide, mainly in terms of meat production, but also of eggs. Other poultry species that have economic importance as meat birds are the domestic duck (*Anas platyrhynchos domesticus*) and turkey (*Meleagris gallopavo gallopavo*), but in terms of research into production, behaviour and welfare, these latter species have been less studied. As a result, information regarding the domestic fowl has often been extrapolated to these species, which may be inappropriate given their different ecological backgrounds.

1.2 The origin, natural habitat and early domestication of ducks and turkeys

1.2.1 The domestic duck

It is generally considered that the common domestic duck originates from the wild mallard *(Anas platyrhynchos)* (Delacour, 1964). The mallard is classified as a dabbling duck or surface feeder belonging to the tribe Anatini in the family Anatidae. This large family in the order of Anseriformes includes most waterfowl. Wild mallards are one of the most numerous and familiar of waterfowl species, and are widely distributed throughout the northern hemisphere (Delacour, 1956 and 1964).

Throughout its range in the wild, the mallard is found on or near most kinds of water, apart from open sea. Most commonly inhabiting freshwater environments such as ponds, lakes, rivers, canals reservoirs, marshes, grassland and arable fields, it also utilises estuaries and brackish bodies of water. Man-made parkland and leisure areas with accessible water are also heavily frequented. Primarily adapted to locomotion on and in water, mallards also walk well on land and are very able fliers, capable of long distance flights. Whilst mallards are not generally considered migratory, in some areas this species locally migrates, with influxes of birds to more inland wintering grounds in the mid-winter months and immigrants from more Northern latitudes (Owen et al, 1986). Wild mallards are omnivorous, feeding on a large variety of food types including aquatic vegetation, grass, algae, molluscs, insects, larvae, small fish, tadpoles and crustaceans, depending on the season, time of day, local availability and lifecycle stage of the bird. The wild mallards' general water-based ecology makes them the most adaptable and opportunistic of waterfowl species (Owen and Black, 1990; McNeil et al, 1992). Aspects of mallard behaviour and ecology will be discussed further in other chapters of this thesis in relation to the anatomy of their visual system and visual capabilities (see Chapter 2).

Clayton (1984) and Hetzel (1986) have both reviewed the early history of the common domestic duck and concluded that it is obscure. Limited evidence points to south-east Asia as the major centre of domestication, although the process has probably been repeated many times elsewhere. Whilst the Egyptians, Greeks and Romans are known to have kept wild birds, including ducks, in captivity there is no evidence of continued

breeding. The earliest reference to domestic ducks in Europe (cited by Delacour, 1964) is as recent as the 12th century, stating that distinctive domestic forms certainly existed by this time. Domestication of ducks in China may date back to at least 3000 years, with archaeological evidence of pottery models of ducks being found, which indicates the possibility of even earlier domestication (Zeuner, 1963). Certainly the duck, with its natural affinity for water, is well adapted to supply meat and eggs in the wetland environment of the paddy fields, swamps, rivers and other waterways of south east Asia.

1.2.2 The domestic turkey

In contrast, the domestic turkey has a more recent history of domestication, and a very different ecological background. The domestic turkey derives from the native wild common turkey of North America (*Meleagris gallopavo).* These large birds belong to the order of Galliformes, along with the domestic fowl *(Gallus gallus domesticus)* and Japanese quail (*Coturnix coturnix japonica),* and are thought to be closely related phylogenetically to the order Anseriformes, which includes the mallard and other waterfowl species (Sibley and Monroe, 1990). Six subspecies of wild turkeys are recognised: Eastern (*M.g. silvestris)*; Florida (*M.g. osceola)*; Rio Grande (*M.g. intermedia)*; Merriam's (*M.g. merriami)*; Gould's (*M.g. mexicana)* and Mexican (*M.g. gallopavo).* Those taken to Europe at the time of the Spanish conquest in the 15th century are believed to be descendants of the Mexican turkey (*M.g. gallopavo).* However, it is likely that some of the other subspecies have also contributed to the genotype of the domesticated turkey at various points in its domestication (Crawford, 1984).

The natural habitat used by wild turkeys varies considerably according to the season, climatic conditions and behaviour being performed. These large gallinaceous birds are land-based, and regularly utilise environments as diverse as open plains, dense mixed woodland, thick scrub, forest clearings and farm fields, often roosting in trees at night. Wild turkeys are capable of flight, but their endurance is not great. Whilst these birds are not migratory they may move up to 80 km between winter and summer sites. Locomotion is mainly through walking and running, and typically 2-3 km may be covered daily in the search for food. The home range of these birds can cover between 200-1000 acres (Schorger, 1966). Wild turkeys are omnivores that feed on a wide range

of food items such as seeds, agricultural grains, berries, leaves, grasses, nuts, insects, larvae and other small invertebrates, from a large number of different plant and animal species, depending on their seasonal and local availability. Wild turkeys are considered by wildlife biologists to be highly adaptable, largely as a result of their varied habitat usage and feeding ecology. Aspects of the general ecology and behaviour of wild turkeys will also be discussed in Chapter 2, sections 2.2.1 and 2.2.2, in an attempt to account for variations in the visual anatomy in comparison to the mallard and common domestic duck.

Schorger (1966), Crawford (1984) and Brant (1998) have published extensive historical reviews concerning the wild turkey and its domestication. Whether the turkey was first domesticated in Mexico, or if captive wild birds were kept is not clear. However, following discovery and introduction to Spain, turkeys became rapidly distributed throughout Europe, and there are reports of turkeys in France by 1538 and England by 1541. Therefore, the domestication of the turkey is generally considered to have taken place in Europe (Brant, 1998). European settlers to Eastern North America in the 17th century brought with them domestic turkeys descended from those taken from Mexico. There is a general consensus in the literature that whilst the Eastern subspecies of wild turkey *M.g. silvestris* had not been domesticated at this time, wild birds were commonly kept. Inter-breeding of the domestic and wild populations resulted in larger and more vigorous hybrids, which were then also exported to Europe. Extensive cross-breeding in Europe and North America of these various domesticated strains of turkeys have contributed to the genotype of the modern domestic turkey.

1.3 Recent history and present status of domestic duck and turkey production

Over the last 50 years, the recent history of duck and turkey meat production has followed similar trends of increasing intensification of production systems, selection for growth rate, increased body size, and improvements in meat quality through reductions in carcass fat. These are detailed below, and the present status, world wide and in the United Kingdom (UK), of these species as meat birds is discussed.

1.3.1 The domestic duck

The domestic duck is now distributed throughout the world, exhibiting many variants in shape, size, colour and specialisation as meat and egg-laying breeds, such as the Pekin, Aylesbury, Khaki Campbell and their numerous strains and hybrids. Desforges and Wood-Gush (1975) studied the main behavioural differences between domesticated ducks and the mallard, attributing those found to the consequences of domestication and associated husbandry. Domestic ducks were found to be less aggressive as they tolerated other birds feeding in close proximity, less wary of humans and novel objects placed in their pens and showed no seasonal territorial behaviour or pair formations during natural breeding seasons. The tendencies to nest-build and brood eggs have also been almost totally eliminated in domestic ducks. These changes all have obvious advantages from a husbandry point of view, but they also suggest that the visual ecology in modern duck housing, and the behavioural requirements of domestic ducks for light will be different from those of wild mallards in their natural habitats (see Chapter 2).

Farrell and Stapleton (1986) combined a series of comprehensive reviews of the production and management systems under which domestic ducks are reared within a number of countries around the world. In extensive systems in China and other Far East countries, ducks are grazed in rice paddy fields, and sometimes production is integrated with fish farming (Edwards, 1986). Semi-intensive methods in these countries involve ducks reared in simple houses made of local materials (bamboo, stone or concrete). These are naturally ventilated, with access to outside pens or a range, and artificial lighting may also be provided (Chen, 1989). Over the past 20 years, the introduction and increasing growth of intensive systems for the production of hatching eggs and meat birds has occurred in countries like China, Thailand and Vietnam. This is due to the increasing pressures on land use, and the importation of high producing breeding stock from the USA and UK (Hetzel, 1986).

Fully intensive production of ducks has only been achieved in the last 40 years, although ducks have been, and continue to be, produced under semi-intensive conditions in many developed countries. Most of the developments towards intensive production have taken place in Europe and North America, with regard mainly to meat

or table ducks. This is accomplished in specially designed buildings, where the environmental conditions are largely controlled in terms of temperature, ventilation, illuminance, light source, light colour and photo-period, sex ratios and stocking density. Traditionally, extensive and semi-intensive methods of production use outside facilities to varying degrees for all or part of the production cycle, and may also include access to ponds or water for swimming and bathing.

Ducks are raised mainly for meat and their eggs have not made a major contribution to human diets, except in some south east Asian countries, where under certain extensive systems, in hot and wet conditions the duck can produce more eggs than domestic fowl and be more disease-resistant (Clayton, 1984). A relatively insignificant by-product of duck production is down and feathers, which are particularly used for human bedding. The duck as a meat producer though, has recently been the subject of intense development. The most notable change has been the increases in growth rate, reflected in live weights of 3.5 kg being attainable by 7 weeks of age by some larger commercial strains (Cherry Valley Farms Ltd, 1999), compared with 9 weeks required 40 years ago. As a consequence of selection for increased body size, the common domestic duck has lost the ability to fly, which is a survival attribute in its progenitor, the mallard. However, it retains its tendency to flock, a characteristic that has been used to advantage in some production systems. Whether the issues of leg weakness and high mortality due to the increased strain of rapid growth on the heart and lungs, which affect broiler chicken and to some extent heavy turkey production, are prevalent in duck production systems is not noted in the literature.

At present the greatest economic importance of the duck remains in south-east Asia as a source of meat and eggs. About 86% of all domestic ducks slaughtered in 2001 were reared in this region, the principal countries being China, Thailand, Vietnam, Republic of Korea, Malaysia, Burma, Indonesia, Bangladesh and the Philippines (FAO, 2003; see Table 1.1) However, ducks are of comparatively minor economic importance in terms of numbers and meat produced compared to the domestic fowl. France, the USA, Germany and the UK are at present the main duck producing western countries, all producing over 40,000 tons of duck meat in 2001 (FAO, 2003; see Table 1.1). In 2001, the proportion of duck meat was 3% of all poultry meat produced in the UK, with an average producer price of 165.7 p/kg carcass weight (DEFRA, 2003). Whilst duck meat

comprises a small proportion of total meat consumption, being marketed in developing countries mainly as a luxury meat product, technological advances in genetic improvement and better designed husbandry facilities are permitting large-scale intensive production that ensures a future for ducks in the agricultural economies of the world.

Table 1.1 Duck and duck meat statistics for the main producing countries in the world in 2001.

World / Main Producing Countries	**Duck population/ stocks (000 head)**	**Slaughtered (000 birds)**	**Production (metric ton)**
World	917,697	2,011,130	2,933,106
China	635,874	1,534,500	2,009,980
France	23,500	82,800	238,000
Thailand	23,000	70,000	105,000
Vietnam	57,000	58,000	69,600
United States of America	6,650	23,000	52,600
Malaysia	13,000	22,000	50,600
Republic of Korea	6,716	24,000	48,000
United Kingdom	4,000	20,500	45,800
Egypt	9,200	16,100	41,860
Germany	1,900	21,100	41,000
Hungary	1,480	11,000	25,100
Burma	6,200	17,790	22,658
Philippines	12,500	11,000	22,000
Mexico	8,100	8,100	20,250
Poland	3,571	7,000	15,000
Netherlands, the	1,020	7,000	14,000
Indonesia	29,905	15,170	13,650
Bangladesh	13,000	13,000	13,000

Source: FAO Statistical Databases (2003).

1.3.2 The domestic turkey

From the 16th to the 20th centuries, turkeys spread throughout the world as domestic birds. During these 500 years of domestication many varieties and strains have been developed. Crawford (1984), Brant (1998) and Davis (2001) have each thoroughly reviewed the social, political, economic events and genetic advancements that led to these developments in turkey production systems. Until World War II, turkeys were

kept in traditional ways. Reproduction was seasonal, using natural and artificial incubation methods. Poults were reared outside, usually semi-feral and were fattened for market in late autumn or early winter. A number of colour varieties were recognised. These birds were larger and heavier than the wild forms, but otherwise were not greatly changed. Since the mid-1950's, a highly efficient turkey industry has evolved. Birds are now normally reared on deep-litter under intensive conditions throughout the year, where environmental factors are largely controlled, in terms of temperature, ventilation, lighting, sex ratios and stocking density, as with most modern broiler fowl and duck production. In free-range systems birds are provided with some access to outdoor areas for a designated period of the production cycle.

The two main market products are a smaller turkey for home consumption and the heavy turkey for institutional use and further processing into turkey meat products. Selection for rapid growth rate and increased body size has resulted in the development of turkeys with greatly hypertrophied breast and thigh muscles. Selection for improved growth rate has allowed reductions in age at slaughter, with live weights of 12.4 kg (female) and 18.5 kg (male) being attained by 20 weeks of age in some modern strains (British United Turkeys Ltd, 1999), thus improving economic performance.

As with domestic fowl and ducks, this selection for increased body weight has had its consequences, resulting in an inability of male turkeys to mate naturally because of their increased body weight. Fertility from natural mating in commercial breeding flocks has declined so drastically that it has become necessary to use artificial insemination. This practice is now universal in the breeding of commercial stocks, and natural mating ability is no longer included in selection programmes for sire lines (Crawford, 1984). The heavier strains of turkeys, particularly heavy breeding and finishing males, can also be pre-disposed to suffer from leg weakness and disorders due to their weight and conformation. This is particularly so when also subjected to poor management conditions such as hygiene and nutritional imbalances (FAWC, 1995). A further consequence of selection for rapid growth rate and increased body size has been the loss of the ability to fly, a consequence of domestication and selection the turkey shares with commercial ducks. Unfortunately, direct comparisons of behavioural differences between wild and domesticated turkeys have not been made, unlike for domestic ducks and fowl.

Another more recent major event in turkey history was the almost universal conversion of commercial turkey stock to white-feathered varieties. Consumers objected to the dark pin-feathers and spots of black pigment left in the feather follicles, especially in the skin over the breast. Although at this time the most popular commercial turkeys were the broad-breasted, bronze birds, within a few short years there was a mass conversion to the rearing of broad-breasted, white turkey strains (Brant, 1998). The vast majority of modern domestic turkeys are from only a small number of strains, most of which have completely white plumage though some retain the bronze wild type appearance. Studies investigating plumage properties with regard to vision and lighting are discussed in Chapters 2 and 3.

Today, turkeys are a major poultry species in the Americas and Europe, with 94% of all domestic turkeys slaughtered in 2001 being reared in these regions (FAO, 2003; see Table 1.2). The principal producing country at present is the USA, producing just under 50% of the world total of turkey meat, possibly due to the association of turkey dishes with the Thanksgiving holiday. Other major turkey producing countries are France, Italy, Germany, the United Kingdom, Brazil, Canada, Hungary and Israel (FAO, 2003; see Table 1.2). In such, countries turkeys are second only to the domestic fowl as a meat bird, in terms of numbers and meat produced. In 2001, turkey meat was 16% of all poultry meat produced in the UK, with an average producer price of 122.1 p/kg carcass weight (DEFRA, 2003). Unlike ducks and domestic fowl though, turkeys are of minor economic importance in Asia, with no production figures available for most Asian countries. In Africa they are only of importance in South Africa, but once again marginally so. Turkey production is likely to continue as a highly intensive industry, despite concerns for limits of biological fitness being reached, loss and exhaustion of genetic variability in breeding stocks and issues of bird welfare. The economic and social importance of the turkey as a food product, as with the domestic duck and fowl, justifies scientific investigation of factors that may influence their productivity, behaviour and welfare.

Table 1.2 Turkey and turkey meat statistics for the main producing countries in the world in 2001.

World / Main Producing Countries	Turkey population/ stocks (000 head)	Slaughtered (000 birds)	Production (metric ton)
World	242,956	656,692	5,122,730
United States of America	88,000	269,000	2,490,000
France	42,000	117,900	750,100
Germany	8,800	34,300	340,000
Italy	25,000	35,000	340,000
United Kingdom	9,500	26,000	258,000
Brazil	9,300	26,600	165,000
Canada	5,000	22,430	149,024
Hungary	3,300	17,000	110,000
Israel	5,000	13,800	90,000
Portugal	7,000	11,500	46,000
Netherlands, the	1,523	8,500	42,000
Argentina	2,800	6,800	34,680
Ireland	1,699	4,800	34,000
Mexico	3,000	8,255	27,242
Austria	700	2,124	24,919
Australia	1,300	6,500	22,800
Spain	1,100	5,500	22,000
Poland	802	4,000	20,000

Source: FAO Statistical Databases (2003).

Chapter 2:

Literature Review – Vision, the Effects of Wavelength and Illuminance on Poultry and Lighting Recommendations

2.1 Avian senses and the physical stimulus for vision

An animal's sensory capabilities are based upon each of their sensory systems properties of detection and response to different forms of physical stimulation. Taste and smell (chemoreception) respond to chemical stimuli. The sense of touch responds to a variety of stimuli including mechanical pressure (mechanoreception), unpleasant or even painful stimulation (nociception), warm and cold temperatures (thermoreception), and also electrical stimulation. The sense of hearing responds to changes in pressure that originate from the vibration of air molecules within a medium such as air or water. The physical stimulus for vision is electromagnetic radiation, which can have wavelengths over a broad range. If electromagnetic radiation produces a visual response in an animal it is usually referred to as "light". However, the section of the spectrum that is perceived by animals is relatively narrow and varies between species (Coren et al, 1979). In humans, the visible spectrum constituting light is conventionally taken to extend from $400 < \lambda < 700$ nm (CIE, 1983), although the range has also been given as 380-750 nm (Figure 2.1). However, in insects, fish, birds and some mammals sensitivity has been shown to be broader, extending into the ultraviolet ($UV_A = 315 < \lambda < 380$ nm) or near infrared ($750 < \lambda < 1400$ nm).

The ability of animals to respond to changes in the external environment depends on the sensory processes that the animal has evolved to detect such changes (McFarland, 1993). Knowledge of sensory functions is therefore important to aid the understanding of behavioural mechanisms, how animals perceive and interact with their environment, and the behavioural needs animals have for environmental conditions. This review describes the avian sense of vision, covering the structure of the avian visual system, the visual capabilities and ecology of birds, including where specific details are known, ducks and turkeys.

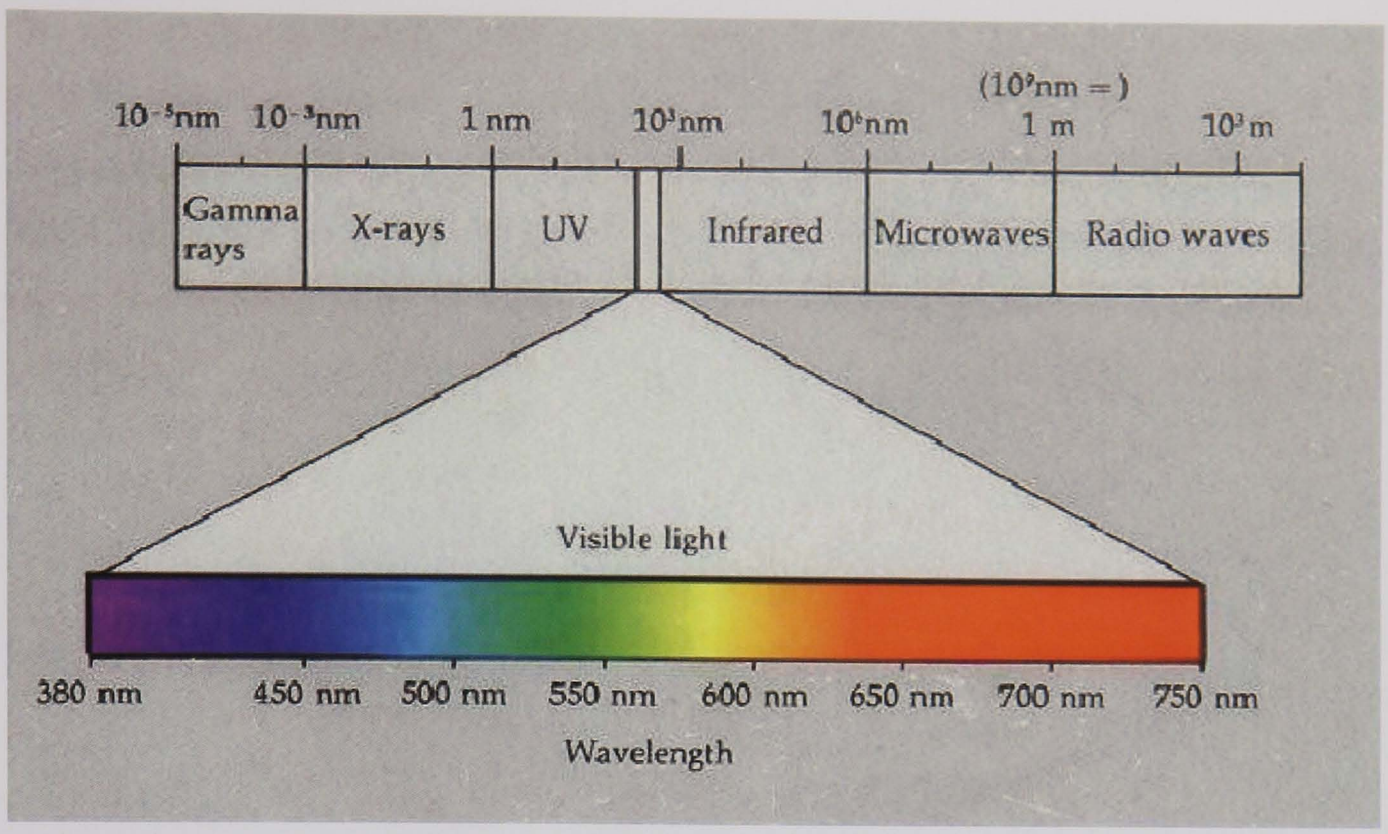


Figure 2.1 The electromagnetic spectrum, emphasising the section considered visible light for humans. Source: Krupp (2001).

2.2 Avian Vision

Birds, along with the majority of other vertebrates, have evolved photon-detecting systems that are also capable of image formation. This provides birds with a visual representation of their external environment, but has also necessitated the development of a major sensory system to process and interpret such sensory input. The visual process in birds, like that in other vertebrate eyes, converts light energy into nerve impulses that are delivered via the optic nerve to the brain for further analysis of the visual images produced (Meyer, 1986). Some structures in the eye such as the cornea, aqueous humour, lens and vitreous body, participate in the refraction of the light rays, producing an image focused on the light sensitive retina. This image causes electrical changes in the retina through the selective absorption of the light rays by specific visual pigments in the photoreceptor cells.

2.2.1 The structure of the visual system in domestic ducks and turkeys

The physical properties of the visual system affect the nature of visual perception. It is therefore of great importance to understand the physiological design of the avian visual system if we are to investigate how a bird perceives light in its external environment.

The morphological features of the avian eye have been comprehensively reviewed by several authors, and has been found to display the basic pattern of organisation found in all vertebrate eyes (see Figure 2.2) (Wood, 1917; Walls, 1942; Duke-Elder, 1958; King-Smith, 1971; Martin, 1985; Meyer, 1986). In the following discussion on the structure of the eye, emphasis will be placed on the structures that are unique to avian species or considered to be responsible or important in determining the particular visual abilities of birds.

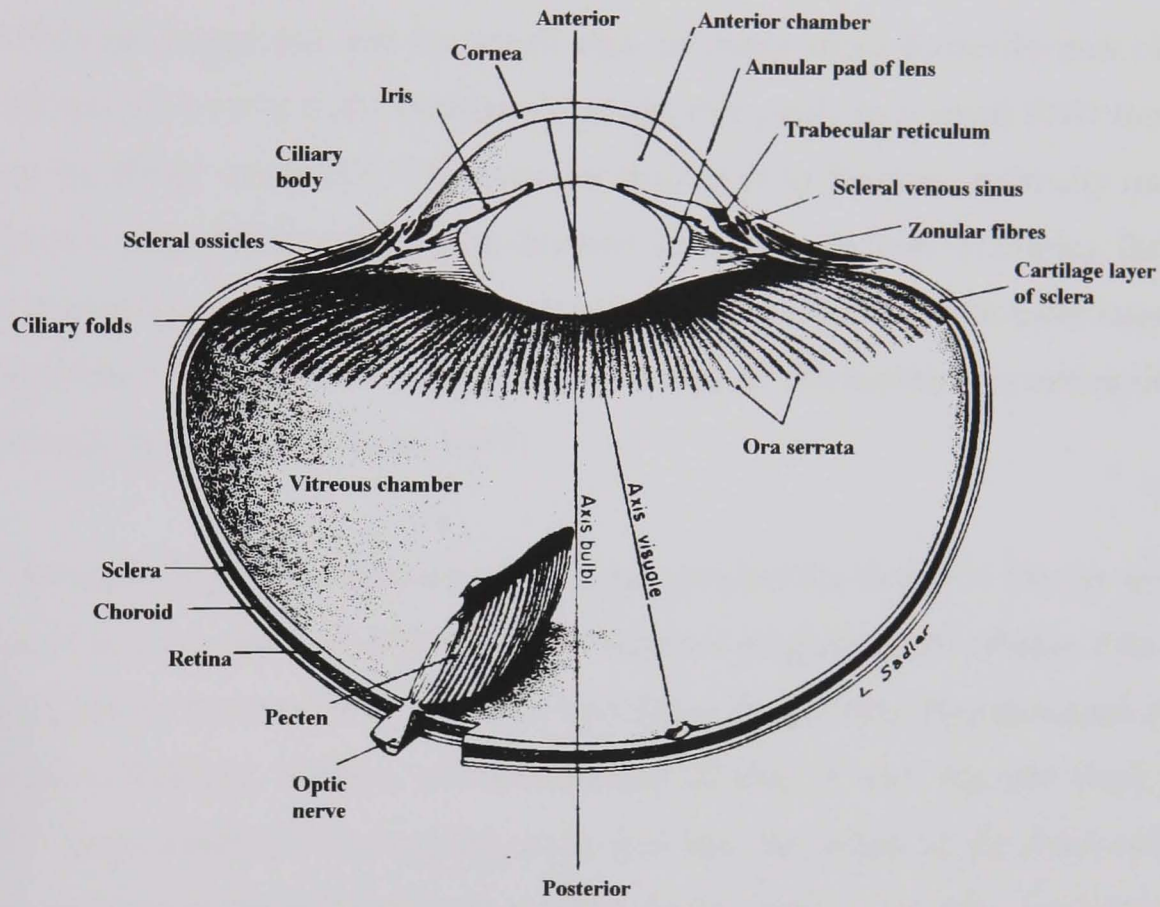


Figure 2.2 The structure of the eye in the domestic fowl. Source: Evans, H.E. (1979).

2.2.1.1 Eye size and shape

The avian eye is large relative to the size of the head and brain. For example, human eyes make up about 1% of the total mass of the head. In comparison the eyes of domestic fowl together weigh about the same as the brain (King-Smith, 1971). Optically, the most important parameter of eye size is the anterior focal length or posterior nodal distance (PND), since this determines the retinal area over which the image of an object is spread. The longer the PND in the eye, the larger the retinal image.

An increase in PND spreads the visual image over more photoreceptors in the retina and determines the resolution of the image. Thus, large eyes, as often seen in nocturnal birds, such as owls (Strigiformes) and active diurnal birds like falcons (Falconiformes), have greater light-gathering potential than smaller eyes due to the larger surface area available for photoreception by the retina. However, increasing diffraction effects and aberrations within the optical system will set limits to image resolution and the adaptive usefulness of eyes larger than those found in such species; since, although the retinal image will be larger, its quality is predicted to deteriorate and the image will be dimmer (Miller, 1979). This parameter of the eye has also been deemed important if the eye is to function adequately throughout a range of naturally occurring illuminance levels. Martin (1985) has suggested that the small eyes of many small Passeriformes cannot function adequately over a wide illuminance range, due partly to a small PND limiting light-gathering ability of the eye. This restricts their eyes to function optimally only in the illuminance range which exists in the daytime. In relation to these examples, the size of the eye in poultry species is generally considered to be neither exceptionally large nor small, suggesting a general level of function in a range of illuminance occurring during daytime through to twilight (Martin, 1999).

As in the domestic fowl and the majority of avian species, the shape of the eye in both the duck and turkey is flat (see Figure 2.2) as opposed to globose or tubular. Flat eyes are characterised by the anterior to posterior axis being shorter than the other axes of the eye. The visual function of these different shapes of eye, if any, has not been fully determined. King-Smith (1971) highlights the fact that the retina of the fowl eye lies close to the position of focus throughout, making the eye almost optically equivalent for all directions of incident light, providing good vision through a wide field of degrees. It has also been suggested that the different avian eye shapes may simply be a solution to the problem of placing relatively large eyes in a small avian skull (Martin, 1985) (see section 2.2.2.3 Spatial acuity).

2.2.1.2 Sclera

The structural shape of the eye is given support by the sclera, which is the whitish layer containing cartilage and dense collagen fibres for this purpose. The ciliary region of the eye (Figure 2.2) is given particular support by the sclerotic plates or ossicles, which are a particular feature of reptilian and bird eyes. These are a group of bones that form a ring of plates surrounding the cornea, providing structural strength and permitting a

more powerful accommodative function (Meyer, 1986). The shape of these ossicles in birds with flat eye shapes, such as ducks and turkeys, are themselves flat or slightly convex (Martin, 1985).

2.2.1.3 Ocular media (cornea, lens, aqueous humour and vitreous humour)

These four components, the cornea, aqueous humour, lens and vitreous humour form the ocular media, which act as refractors and intraocular filters of the light passing through the eye. As light enters the eye it is refracted by these structures. This is because the light passes through mediums of different density where its speed is altered. The amount of refraction depends on the indices of refraction (defined as the speed of light in vacuum divided by the speed of light in the medium) of the two media light passes from and to. This refracted light then forms an inverted image on the retina. The principle refractive components in the avian eye are the cornea and the lens. The cornea is curved in structure and forms the front surface of the eye, and appears to be of uniform thickness. It acts as a simple lens; when the Crampton's portion of the ciliary muscles contract the curvature of the cornea is altered. Corneal accommodation has been studied in the mallard and will be discussed later in this review (section 2.2.2.1 Accommodation).

The more complex, biconvex lens is situated directly behind the iris, and may be divided into two components. The central body of the lens is formed by layers of fibres which decrease in their density from the central core, thus producing a gradient of refractive index. This part is surrounded by the annular pad, which is a feature found only in the avian and reptilian lens (Walls, 1942). The whole avian lens is in constant contact with both the ciliary body and the iris. Lenticular accommodation is achieved by the compression of the lens by the contraction of the Brücke's part of the ciliary muscles attached around its circumference, thereby thickening the lens. The function of the annular pad is disputed, but Walls (1942) suggested that it functions as part of the accommodative mechanism. Its relative size appears to vary between species, as does that of the central body of the lens. These variations in the annular pad and lens are presumably reflected in differences in refractive power, accommodative range and visual fields of the eye between species, but it is yet unknown with which optical or ecological features these size differences correlate (Martin, 1985).

The anterior chamber of the eye between the cornea and the lens is filled with a proteineous substance, the aqueous humour. The vitreous humour is contained in the posterior chamber. In domestic fowl, this humour is watery, but more refractive than the aqueous humour. The purpose of these fluids is to maintain the shape of the eye, but along with the cornea and lens they also act as intraocular filters of the light prior to it reaching the retina. The ocular media are often presumed to be spectrally transparent to UV light, and this has been shown to be the case in the pigeon and the fowl (Govardoskii and Zueva, 1977). In the turkey, the ocular media transmits UV_A wavelengths down to λ=315 nm, with 50% transmission occurring at λ=358 nm (Hart et al, 1999). However, Jane and Bowmaker (1988) found that the ocular media of the duck eye starts to strongly absorb short wavelengths below λ=400 nm with transmission falling to 50% at λ=370 nm and 1% at λ=340 nm. This has implications for vision in the UV for these species and will be further discussed below (section 2.2.2.5 Photopic spectral sensitivity).

2.2.1.4 Iris

The iris is a muscular structure surrounding the pupil, which controls the amount of light entering the eye. The muscles of the iris (the *sphincter pupillae* and the *dilator pupillae*) are striated and it is these muscles that are partly responsible for the rapid pupillary response seen in birds compared to mammals (Barbur et al, 2002) (see 2.2.1.5 Pupil). The anterior surface of the iris is heavily pigmented with melanin pigment in the stroma combined with the underlying pigment of the epithelial layer of the iris (Daugman, 2000). Iris colour in vertebrates was reviewed by Mann (1931; cited by Martin, 1985) and described as being usually yellowish brown in domestic fowl and turkeys. In domestic ducks, the iris is noted as dark brown in colour (Jane, 1986). There is no literature for birds on the effect of the colour of the iris on visual ability, but some studies in rats suggest that reduced melanin in the iris allows more light through to the retina, i.e. blue eyes are more sensitive to light than brown eyes, and albino eyes are markedly more sensitive (Shear, O'Stean and Anderson, 1980).

2.2.1.5 Pupil

The pupil aperture in poultry species is spherical, and is situated between the cornea and the lens, at the centre of the iris. The pupil seen when looking into the eye is magnified by the cornea. One role of the pupil is to regulate retinal illumination. Therefore, a wide pupil can prepare the avian eye for dark adaptation and a small pupil can protect the eye from possible photic damage from high illuminance levels (Woodhouse and Campbell,

1975). In humans a pupil diameter above 2.4 mm deteriorates image quality, whilst in Falconiformes image quality is limited at larger pupil diameters (Miller, 1979). Pupil response as mentioned above is much faster in birds than mammals. In fowl, the much shorter neural pathway involved is considered to contribute to this fast response. Factors other than the light reflex pathways, that mediate luminance responses, have also been shown in fowl to trigger pupil responses. Barbur et al (2002) showed that the pupil of fowl responds to stimulus colour, and particularly a red stimulus, but not to a green or spatially structured stimulus (sinusoidal gratings). Pupil responses have not been reported in ducks and turkeys.

2.2.1.6 Eye position

The eyes of ducks and turkeys are both laterally placed within the skull. In the mallard the placement is more lateral than in the pigeon (Martin, 1986), and is therefore assumed to be more lateral than in the turkey or fowl too. This implies a difference between ducks and turkeys in their visual abilities, as the position of the eye in the skull defines the binocular (frontal) and monocular (lateral) fields of vision. Investigations into the visual fields of mallard and fowl have been made and will be discussed with regard to ecology in section 2.2.2.2 Visual fields.

2.2.1.7 Eyelids, nictitating membrane, lacrimal apparatus and eye musculature

Closure of the eyelids in birds is due mainly to the movement of the lower lid to meet the upper, and is controlled by three muscles. The nictitating membrane, or third eyelid, is situated underneath the external eyelids. Two striated muscles are responsible for its movement, the *pyramidalis* and *quadratus* muscles. Whilst it has been proposed that this membrane may have a refractive function in diving birds (Ischreyt, 1912; cited by Martin, 1985), it is less transparent in dabbling ducks such as mallard from which domestic ducks originate. Its function is now considered to protect the eye, ensuring maintenance of the optical quality of the cornea. The gland of the nictitating membrane (*glandula membranae nictitantis*) and the lacrimal gland form the lacrimal apparatus that provides secretions of lubricant to moisten the eye.

2.2.1.8 Retina

The retina, a hemisphere of neural tissue upon which is mapped an image of the visual environment, is now considered an extension of the brain (Collin, 1999). There have been many general histological analyses of the avian retina (see Duke-Elder, 1958;

Morris and Shorey, 1967), and many of these conclude two principle facts about the structure of the avian retina. Firstly, that compared with the retina of other vertebrates, in birds the retina is relatively thick. This increased thickness is attributed to the density and complexity of cells in the various layers of the retina. Secondly, the avian retina is considered highly ordered, with the principal cell layers being clearly distinguishable. The complexity of the interconnections in the avian retina has been thought to demonstrate that a significant amount of intra-retinal visual processing may occur in birds (Rodieck, 1973). In primate visual systems, complex processing occurs in higher forebrain areas, and this may be an important difference between the visual systems of birds and humans, possibly explaining the excellent visual discrimination in birds given the relatively small size of the avian brain (Husband and Shimizu, 2001).

The retina is divided into two major layers, the outer pigmented layer and the inner sensory layer. The non-sensory pigmented layer of the retina, also referred to as the choroid, is a highly vascular and heavily pigmented layer of tissue. Its primary function is to provide a blood supply, and thus nutrition, to the avascular sensory layers of the retina (Martin, 1985), along with the pecten (see section 2.2.1.9 Pecten). The heavy pigmentation of the choroid also acts to reduce reflections within the eye.

The structure of the sensory layer is usually divided further into five major layers, the outer and inner nuclear layers, the outer and inner plexiform layers and the ganglion cell layer. Within these layers five classes of retinal neurons are recognized, the photoreceptor, bipolar, horizontal, amacrine, and ganglion cells (Figure 2.3). This basic organisation forms a pathway for the light-induced nerve impulses to reach the optic nerve.

2.2.1.8.1 Photoreceptor cells

The avian retina is characterised by three types of photoreceptors: rods, single cones and double cones, which can be classified according to their shape. In comparison, humans only possess two, rods and single cones (King-Smith, 1971). The cones and double cones may be further characterised by the presence of an oil droplet within the inner segments of these cells in most birds, including poultry species (see section 2.2.1.8.1*iii* oil droplets). The outer segments of the photoreceptor cells contain stacks of membranous discs, which contain the photosensitive visual pigments (see section 2.2.1.8.1*iv* visual pigments).

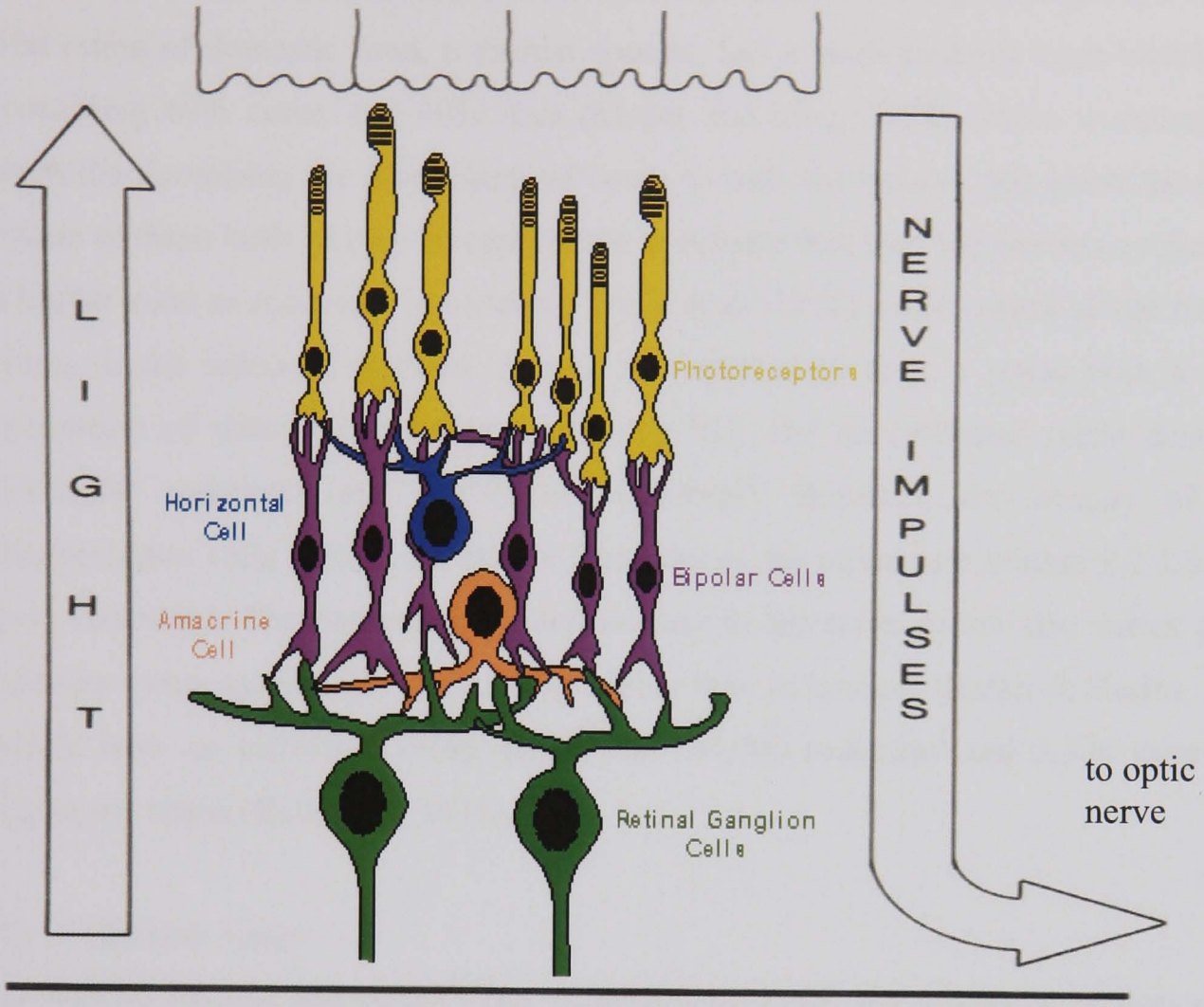


Figure 2.3 A diagrammatic representation of the avian retina, showing the five classes of retinal neurons. Sources: Meyer (1986); Husband and Shimizu (2001).

(i) Rods and single cones

Rods and cones are highly specialised visual neurones designed to transduce the energy from photons absorbed by the visual pigment in their outer segments, into the neural impulses that ultimately result in visual perception. The outer segments of these photoreceptors are typically cylindrical in a rod cell and conical in single cone cells. Rods are concerned with dim-light, or scotopic vision, and are very sensitive to light, functioning primarily in low levels of illumination. Cones in comparison are responsive in bright-light, serving photopic vision and playing a role in both colour discrimination and visual acuity (Meyer, 1986). In most bird species, single cones contain oil droplets, whereas none are found in avian rods which do not contribute to avian colour vision.

The retinas of diurnal birds are characterised by a high number of single cones to rods, whilst the retinas of crepuscular and nocturnal species show a higher proportion of rods. The retina of domestic fowl, a diurnal species, has a predominantly cone-based retina containing 60% cones and 40% rods (Meyer and May, 1973). There is currently no literature describing the proportions of cones to rods for turkeys, but given the diurnal nature of these birds, it may be appropriate to assume that they too possess a retina with a higher cone to rod ratio. In contrast, Wells et al (1975) made counts of the rods and cones in the retina of mallard, finding this species to have a retina with a higher proportion of rods (60.3%) than cones (39.7%), and an estimated mean density of 2,913,000 rods/mm^2 and 1,914,000 cones/mm^2. However, the density of these photoreceptor cells varies in different locations of the retina (see section 2.2.1.8.4 The *area centralis*). The photoreceptor cell density in the avian retina also varies greatly between avian species, but is generally higher than in humans (Butler & Hodos, 1996), which have an estimated mean density of 104,000 rods/mm^2 and 5,300 cones/mm^2 across the retina (Østerberg, 1935).

(ii) Double cones

As well as the rod and single cone photoreceptor cells, the retinas of poultry species also possess double cones, forming a mosaic pattern with single cones. These photoreceptors consist of a principal cone that is similar in structure to a single cone, and an accessory cone which is shorter and broader. Approximately 45 – 50 % of all cones in the retina of fowl are double cones (Morris and Shorey, 1967; Bowmaker and Knowles, 1977). In ducks, double cones have also been shown to represent approximately 50% of the total cone population (Jane and Bowmaker, 1988), and Hart et al (1999) found that the number of photoreceptor cells in the turkey retina were consistent with other studies of Galliformes. The function of double cones is still unknown. Although these receptors in fowl (Bowmaker and Knowles, 1977), ducks (Jane and Bowmaker, 1988) and turkeys (Hart, 1999) contain visual pigment and oil droplets in the principal member, they are not thought to contribute to colour vision. Alternative functions such as the detection of polarised light (Martin, 1985) and as a brightness detector have been proposed (Osorio et al, 1999).

(iii) Oil droplets

Colourless oil droplets are reported in a wide variety of non-primate vertebrates, whilst coloured oil droplets are only found in the cones of birds and reptiles (Walls, 1942;

Muntz, 1972). Such oil droplets are brightly and variously coloured due to the presence of dissolved carotenoid pigments of a dietary origin. The structure and stereochemistry of these carotenoids has been determined (Davis et al, 1984), and it appears that those found in the domestic turkey, goose, fowl and duck are qualitatively the same. On the basis of the colours exhibited by oil droplets, they can be roughly classified into six groups, red, orange, yellow, pale green, clear and spectrally transparent (Goldsmith et al, 1984). These oil droplet types are found to associate primarily with a specific type of visual pigment; red, orange and pale associate with long wavelength sensitive pigments (LWS), yellow with medium wavelength sensitive pigments (MWS), clear with a short wavelength sensitive pigment (SWS) and transparent with the violet/UV sensitive pigment (VS/UVS) (see section 2.2.1.8.1*iv*) (Hart, 2001a; 2001b). However, other combinations have been reported in small numbers (Jane and Bowmaker, 1988).

Oil droplets are positioned at the distal end of the inner cone segments, covering most of the width of the cone. Light passes through, and is selectively filtered by the oil droplet, before entering the photosensitive outer segment containing the visual pigment. Thus, oil droplets are widely thought to play a crucial role in avian colour vision by acting as cut-off filters, absorbing light below their characteristic wavelengths of transmission and conveying longer wavelengths to their associated visual pigments. This has a net effect of shifting maximal sensitivity towards longer light wavelengths. Whilst it has been demonstrated by behavioural tests in Japanese quail possessing carotenoid-free (colourless) oil droplets that such pigments are not essential for colour vision (Kovach et al, 1976), it has been suggested that their aid in the creation of narrowband sensitivity channels by oil droplets with these, enhances colour discrimination in natural conditions where broad-bands of wavelengths are reflected from objects (Barlow, 1982; Govardovskii, 1983; Vorobyev, 2003). Other theories of oil droplet function suggest a role in the reduction of chromatic aberration attributable to shorter wavelengths (Walls, 1942) or the mediation of illuminance discrimination (Kovach et al, 1976).

Five types of oil droplet have been distinguished in the duck (Jane and Bowmaker, 1988) and the turkey (Hart et al, 1999) and their transmission values are displayed in Table 2.1. This number of oil droplets is also found in many diurnal birds (Goldsmith, 1984; Hart, 2001a; 2001b) and domestic fowl (Bowmaker and Knowles, 1977; Bowmaker et al, 1997). Comparison of oil droplet transmission values between species

is often hindered by the different terminology and analysis of cut-off wavelengths by researchers (Partridge, 1989), as seen in Table 2.1.

Table 2.1 Transmission values (nm) of the oil droplets identified in the duck and turkey.

Species	**Transmission values (nm)**						
	Red (R)	**Orange (O)**	**Yellow (Y)**	**Pale (P)**	**Clear (C)**	**Trans-parent (T)**	**Principle Double Cone**
Mallard [a]	580		515	475	450	<390	
Domestic duck - Aylesbury [a]	580		515	500	450	<390	
Domestic duck - Khaki Campbell [a]	580		515	475-500	450	<390	
Domestic turkey [b]		514	490		437	<330	436

[a] Jane and Bowmaker (1988) microspectrophotometry - wavelength at 50% transmission of maximum absorbance.

[b] Hart et al (1999) microspectrophotometry - cut-off wavelength λ_{cut} (nm) – defined as the wavelength of intercept between the line tangent to the absorbance curve at 50% transmission and maximum absorbance.

To date, many studies have investigated the spectral absorption and distribution of oil droplets in numerous avian species, and many of these are reviewed by Hart (2001a; 2001b). These show that retinal oil droplets are distributed amongst avian species in widely differing ratios and patterns. Many of these studies combine the study of oil droplets and their associated visual pigments as it is the interactions of these and their distribution in the retina which influence colour visual ecology. The distribution of the combinations of oil droplets and visual pigments in poultry is discussed below, with particular reference to the possible correlations of these aspects of photoreceptor complement and colour visual ecology (see section 2.2.2.5 Photopic spectral sensitivity).

(iv) visual pigments

The outer segments of the photoreceptors each contain a single type of visual pigment, which are responsible for the absorption of incident light upon the retina. Visual pigments comprise a single opsin protein and a carotenoid chromophore. The commonest chromophore in birds is retinal, the aldehyde derivative of vitamin A_1.

When a chomophore absorbs light it isomerizes, causing the opsin to change conformation and to result in the excitation of the photoreceptor.

Most birds have one rod opsin and four types of cone opsin in their retinas, differentiated by amino acid sequences. It is these cone opsins which are the main source of variability in the peak absorbance of wavelengths (λ_{max}) by each type of cone visual pigment. Cones can be characterised by the locations of their visual pigment spectral sensitivity maxima (λ_{max}) as: very short (VS/UVS or violet/UV), short (SWS or blue), medium (MWS or green) and red wavelengths (LWS or red). Each of these visual pigments is found to associate primarily with a specific type of oil droplet, as discussed above (section 2.2.1.8.1*iii*). All the avian rod visual pigments examined to date absorb maximally (λ_{max}) in the range of $490 < \lambda < 508$ nm, the majority being in the range of $500 < \lambda < 506$ nm (Martin, 1985). Therefore, the visual pigments of avian rods are relatively constant in their spectral location, and do not seem to vary with the ecology of the species (Meyer, 1986).

Five types of visual pigment have been identified in the duck (Jane and Bowmaker, 1988) and the turkey (Hart et al, 1999), a single class of rod and four classes of single cone pigments. In both species the visual pigment of the double cone is the same type as that of the LWS cone visual pigment. The maximum absorbance of wavelengths (λ_{max}) by each type of cone visual pigment is displayed in Table 2.2. The identification of four classes of single cone visual pigments demonstrates that these birds possess the potential for tetrachromatic colour vision ranging from the red to the UV parts of the spectrum. This has implications for the colour visual ecology of these species and is discussed further below (section 2.2.2.5 Photopic spectral sensitivity).

2.2.1.8.2 Bipolar, horizontal and amacrine cells

The structure and responses of the bipolar, horizontal and amacrine cells of the inner nuclear layer of the avian retina (Figure 2.3) are not as well described in the literature as the photoreceptors, as it has been largely assumed that these neuron cells are similar across all vertebrate groups (Martin, 1985). Horizontal and amacrine cells, form synaptic contacts which mediate the lateral spread of nerve impulses in the retina. The horizontal cells make synaptic contacts with the photoreceptor and bipolar cells in the outer plexiform layer, whilst in the inner plexiform layer the amacrine cells make contact with the bipolar and ganglion cells (Husband and Shimizu, 2001).

Table 2.2 Rod, single and double cone visual pigments identified in ducks, turkeys fowl and the human

Species/Breed	Rod Pigment λ_{max} (nm)	Single Cone Pigment λ_{max} (nm)				Double Cone Pigment λ_{max} (nm)	
		VS violet	SWS blue	MWS green	LWS red	Principal	Accessory
Mallard [a]	505	415	452	506	567	567 [h]	567 [h]
Domestic duck - Aylesbury [a]	504	415	449	501	570	570 [h]	570 [h]
Domestic duck - Khaki Campbell [a]	505	426	456	501	570	570 [h]	570 [h]
Domestic turkey [b]	504	420	460	505	564	564 [h]	564 [h]
Domestic turkey [c]	504	-	-	-	562	-	-
Domestic fowl [d]	503	415	455	508	571	-	-
Domestic fowl [e]	507	413	467	507	562	-	-
Domestic fowl [f]	505	418	455	507	569	569 [h]	569 [h]
Human [g]	496	-	419	531	558	-	-

[a] Jane and Bowmaker (1988) microspectrophotometry.

[b] Hart et al (1999) microspectrophotometry.

[c] Crescitelli et al (1964) pigment extracts.

[d] Yoshizawa (1992) biochemical methods.

[e] Govardovskii and Zueva (1977) electrophysiology.

[f] Bowmaker et al (1997) microspectrophotometry.

[g] Dartnell et al (1983) microspectrophotometry.

[h] LWS pigment found in both members of the double cones, but no oil droplet found in the accessory member, just in the principal member. Other studies do not detail visual pigments in the double cone.

2.2.1.8.3 Retinal ganglion cells

Many types of retinal ganglion cells have been distinguished showing a diverse range of morphological features and response properties. In birds, the retinal ganglion cells possess very complex receptive fields, some of which exhibit large responses to horizontal or vertical stimuli, and others to stationary or moving edges, suggesting specialisation of these cells for the detection of different types of movements (Meyer, 1986). Pettigrew (1978) suggests that the level of complexity of these receptive fields is related to the extent of the binocular visual field in birds, i.e. in avian species with laterally-placed eyes like poultry the complexity of the retinal ganglion cells receptive field responses are greater than for an owl species with more frontally-placed eyes.

There are also large differences between species as to the number, types and distribution of the retinal ganglion cells; for example, in humans there are 1 x 10^6 of these cells compared to more than 2 x 10^6 in the retina of chicks, pigeon and quail (Thompson, 1991). Regional differences of retinal ganglion cell distributions within the retina are well noted (Ehrlich, 1981). High retinal ganglion cell densities have been associated with the high densities of single cones, which in turn are equated to areas of high visual acuity in the retina (see section 2.2.1.8.4 The *area centralis;* section 2.2.2.3 Spatial acuity).

2.2.1.8.4 The area centralis

Areas and foveas are regions of acute vision found in the retinas of most birds, and are thought to enhance the resolving power of the eye. An *area* is part of the retina with high cone density and very few rods, if any. Foveas, when found in the retina, are located within an *area* and have an even greater cone density and radically displaced cells of the more internal layers of the retina. This leaves a depression on the outward facing side of the retina, allowing a virtually unobstructed pathway for light entering the eye to the photoreceptor layer. In domesticated poultry, the trend is towards an afoveate state, with fowl possessing instead an *area centralis*, located in the central region of the retina above the optic nerve and pecten (Morris, 1982). This region is less specialised than a fovea, but it has the highest density of cone photoreceptors and the lowest convergence ratio of these receptors per ganglion cell at this site. Ehrlich (1981) found that the *area centralis* has two extensions, central and lateral, in the domestic chick which has implications for the use of acuity by these birds in different parts of their visual field (see section 2.2.2.3 Spatial acuity).

2.2.1.9 Pecten

The pecten is a highly vascularised and heavily pigmented structure in the avian eye. It projects from the retina into the vitreous humour at the point of exit of the optic nerve, and has long been of interest to investigators, both in terms of its elaborate morphology and its potential function. Several functions have been suggested for the pecten including regulation of intraocular pressure, light absorption, perception of movement, shade against glare of the sun and as a magnetic sensor during orientation and navigation (Meyer, 1986). However, the main function of the pecten is considered to be nutritional, and there is much evidence for this theory. The avian retina is devoid of blood vessels, and the capillaries of the pecten are separated from the vitreous humour

only by 1μm, allowing diffusion of oxygen and nutrients to the retina (Bellhorn and Bellhorn, 1975). To further support this, Wingstrand and Munk (1965; cited by Meyer, 1986) observed that in eyes with a non-functional or diseased pecten there were also signs of marked retinal degeneration.

The size of the pecten and the number of pleats do not necessarily coincide with the size of the eye, but appear to be directly related to the behaviour of the bird toward illumination and its general level of activity. Active, diurnal birds with high visual acuity and monocular vision tend to possess a larger and more pleated pecten, and nocturnal species a smaller one of similar morphology (Meyer, 1986). The pecten has been investigated in both the domestic fowl and the mallard. Domestic fowl have a relatively high number of pleats, 16-18 (Kiama et al, 2001), whilst the mallard has a much lower number, 12-14 (Braekevelt, 1989), in keeping with the diurnal nature of fowl and the occurrence of crepuscular and nocturnal activity recorded in wild mallards (McNeil et al, 1992). There is currently no literature describing the pecten in turkey eyes, but given that these birds in the wild are considered diurnal, then it may be hypothesised that the pecten would have more pleats in its structure than that of a mallard.

2.2.1.10 Visual neural pathways and post-retinal processing

Visual impulses from the retinal ganglion cells exit the eye via the optic nerve. The optic nerve fibres from the two eyes converge, almost crossing over completely, and then proceed to carry nerve impulses from the left and right eyes to visual centres in the brain. In birds, these optic nerve fibres follow one of two major pathways, the lateral or medial pathways (Meyer, 1986). The lateral optical tract is considered to be the dominant visual pathway in lateral-eyed avian species like the pigeon, and thus possibly in poultry too (Husband and Schimizu, 2001). In this pathway nerve fibres terminate in the *optic tectum*, which possesses cells which are important for motion processing. From here there are efferents to the *nucleus rotundus* of the dorsal thalamus, which also exhibits motion-processing regions. Neurons in the *nucleus rotundus* then send visual information to the *ectostriatum*, part of the cerebral hemispheres of the forebrain associated with visual integration, pattern and visually controlled defensive reflexes.

In the second pathway, the medial optic tract, fibres are carried to the dorsal thalamus. The optic fibres enter the left and right *lateral geniculate nuclei* of the thalamus, which

also has connections to the hypothalamus. From the *lateral geniculate nuclei*, efferents travel to the *hyperstriatum*, another part of the forebrain associated with vision. In birds there is a positive correlation between the extent of this later pathway and the degree of binocular vision. In birds such as owls (Katen et al, 1973; cited by Husband and Schimizu, 2001) this pathway is more extensively developed, and it is the major visual pathway in humans (Bartleson, 1984).

2.2.2 *Avian visual abilities and visual ecology of ducks and turkeys*

As briefly detailed in Chapter 1 (section 1.2) the ecological background of the progenitors of domestic ducks and turkeys differs in several ways. Vision in wild mallard and turkeys presumably evolved to function in the natural range of light environments that prevailed in these birds' natural habitats. The spectral composition and illuminance in these habitats would affect the availability and quality of information received through the birds' visual system about its external environment. Anatomical and optical constraints obviously provide a set of limitations upon the visual system and its functioning. However, evolutionary processes have produced eyes and visual abilities in avian species that are closely associated with the visual problems of specific lifestyles and ecology. This section reviews work that has attempted to account for variations in the optical structure and visual abilities of the birds' eyes in terms of general ecology and behaviour. The findings of some of these studies have implications for the interaction of poultry vision with the light environment found in their commercial housing, although not all of a bird's visual abilities are of equal importance in this context (Prescott et al, 2003). How the commercial light environment may limit these visual abilities will be highlighted, but the effects of these interactions are discussed further in section 2.3 The effects of wavelength and illuminance on the production, health and behaviour of poultry.

2.2.2.1 Accommodation

Accommodation is the ability to adjust, or focus, the eye so that objects at varying distances from the retina can be seen as a sharp image. To achieve this, the eye must refract light, and to see close objects a greater degree of refraction is required than to see them in focus further away. The degree to which the eye can adjust its refractive power is referred to as its accommodative range, measured in dioptres (D). The mechanism of accommodation in birds varies between species in the relative

contributions of the cornea and the lens to the total refractive power of the eye (Martin, 1985). The refraction of light through the change in the curvature of the cornea, or corneal accommodation, has been studied in the mallard and pigeon. Levy and Sivak (1980) found a mean change of 5 D in accommodation, but no change in the corneal curvature in birds given nicotine sulphate to induce this. Thus, they concluded that accommodation in these two species was primarily lenticular. Lenticular accommodation is the refraction of light through the compression and thickening of the lens, and is considered to be the primary accommodative mechanism in most birds, particularly in those species that employ vision in both the air and water (Levy and Sivak, 1980). In comparison, both corneal and lenticular accommodation in fowl increases the refractive power of the eye by up to 8 D (Schaeffel and Howland, 1987).

The accommodative range of turkeys has not been determined, but in fowl whose eye structure does not greatly vary to that of the turkey, the refractive power of the unaccommodated eye is 80 D, increasing to 96 D when focussing closely on an object. This accommodative range of up to 16 D is greater than the 8 D of humans. Such powerful refraction enables fowl to clearly focus an object at very small viewing distances, such as those used when foraging. This accommodative range is also enhanced by the lower-field myopia found to occur in these birds, allowing fowl to focus on objects on the ground whilst focusing simultaneously on objects further away in the upper-field (Schaeffel et al, 1994). Such visual ability enables fowl to forage and maintain vigilance for possible predators. In comparison, ducks are reported to be able to change the refractive power of their eyes by up to 50 D (Sillman, 1973). As ducks feed by "dabbling" at the surface of water, and sometimes "up-ending" to feed from the bottom of ponds, this ability is required to compensate for the loss of refraction of the cornea when the eye is immersed in shallow water.

For ducks and turkeys reared in intensive commercial housing, the ability to accommodate will be used in different ways to wild birds. For example, ducks housed indoors rarely have the opportunity to immerse their heads in water, and so the ability of the duck eye to accommodate underwater is often unused. However, accommodation is important to enable these birds to extract visual information from their environment, aiding them to locate resources such as food and water, to navigate around their housing area, and for recognition of conspecifics and their intent. The ability of the eye to accommodate can be affected by the light environment during rearing. Refractive errors

can be induced in fowl (Li et al, 1995) as can bupthalmia in turkeys (Thompson, 2001) when they are reared under prolonged or constant photoperiods, particularly if they are used in combination with dim or bright illuminance. Lighting conditions that can cause such effects will clearly hinder the ability of the birds to accommodate. The effects of this are discussed in section 2.3.3.2.

2.2.2.2 Visual fields

The angle or field through which a bird can see without moving its head is referred to as the birds' visual field, and is determined by the position of the eyes in the skull and their shape. Humans have a total visual field of only 180° degrees, but have a wide binocular field of 120° (Gelatt, 1999). In fowl and turkeys with eyes that are laterally placed and flat in shape, their total visual field is more than 300°. The degree of binocular vision is relatively small, not exceeding 30°, and is positioned such that the beak lies approximately at the centre of the binocular visual field. This is a feature that is seen in species which feed by visual guidance of the bill directly towards individual objects (Martin, 1999), such as the pecking at individual grains and pellets observed in fowl and turkeys. The visual field of the mallard has also been studied (Martin, 1986) but shown to be quite different to that of fowl and turkeys. The eyes of mallard are more laterally placed in the skull, and this gives the bird a visual field of 360° in the horizontal plane and a narrow binocular field of 20°, extending vertically through 220° from the bill to directly behind its head, enabling the bird to see behind it. The bill falls just within the periphery of the visual field, and this is a feature of birds which do not need to monitor their bill position visually when foraging (Martin, 1986; 1999). This correlates with evidence that the foraging of these birds can be guided exclusively by tactile and taste cues rather than vision (Martin and Lett, 1985; cited by Jane, 1986), and the fact that mallard show crepuscular and nocturnal activity in the wild (McNeil et al, 1992). It also suggests that ducks use visual cues differently to turkeys and fowl when feeding, which may have implications for the effects of lighting on feeding behaviour in commercially reared birds.

2.2.2.3 Spatial acuity

The ability to distinguish the detail of visual objects is known as the resolving power of the eye, or acuity. The acuity of a bird's visual system depends on the density and distribution in the retina of the rods, cones and retinal ganglion cells. Psychophysical tests using gratings are often used to measure acuity, with the limits of resolution

defined as the finest grating that can be distinguished from an isoluminant grey stimulus. Such methods have not been used to measure the acuity of ducks or turkeys, but in fowl, acuity has been measured variously as 1.5 (Over and Moore, 1981) and 4-6 cycles/degree (DeMello et al, 1992). However, Schmid and Wildsoet (1998) estimated the visual acuity at between 6-8 cycles/degree, giving support to the higher resolutions for fowl. In comparison, human acuity has been measured as 30 cycles/degree (Spence, 1934) (cited by Prescott et al, 2003). Non-behavioural methods have also been employed to assess acuity giving theoretical resolution limits based on the posterior nodal distance (PND) of the eye and peak cell density counts (see Hart, 2002). These studies suggest a lateral visual field acuity of 7.1 cycles/degree for fowl (Donner, 1951; cited by Hart, 2002) and 20.6 cycles/degree for peafowl (Hart, 2002). This different is attributed to the longer PND of the peafowl eye (see section 2.2.1.1 Eye size and shape).

Other aspects of eye structure may possibly account for the higher acuity of humans compared with Galliformes. Humans also possess a fovea, whilst the *area centralis* of poultry species is associated with high acuity through increased cone and ganglion cell density. The relatively flat shape of the eye in these birds means that images are equally well focused upon most areas of the retina in fowl, and not just upon the area of the fovea as in humans (King-Smith, 1971). Therefore, the eye of poultry is better adapted for good acuity around the majority of its field of vision than the human. This ability would certainly aid predator detection in fowl.

The density and distribution of retinal ganglion cells can represent the ecology and habitat of a species. Ehrlich (1981) found that the *area centralis* in domestic fowl chicks has two extensions with increased densities of ganglion cells. The central extension receives images from just above the centre of the eyes' field of view, and may be used for the detailed imaging of objects in the upper visual field, such as possible predators. The lateral extension runs in a band from this point down towards the beak, and may be involved in the imaging of objects in the lower myopic field, such as food (Ehrlich, 1981). In comparison, Hart (2002) found that peafowl have a single *area centralis* with no such extensions of increased ganglion cell density. These birds have a feeding ecology more like that of the turkey, foraging on open plains and scrubland for more substantially sized items, than red jungle fowl which prefer small food items such as seeds and grasses. It is suggested that the larger food objects taken by peafowl do not require the specialised regions of high spatial acuity as seen in the retina of fowl (Hart,

2002). Unfortunately, there has been no comparable work on the duck or turkey on this subject.

Under commercial light conditions illuminance could affect the visual acuity of poultry species. Acuity in the diurnal pigeon has been shown to fall under light conditions that result in scotopic vision being used (Hodos and Leibowitz, 1977). Like fowl, and possibly turkeys, these birds have a high proportion of cones to rods in the retina. For ducks with their higher rod to cone ratio, this may not be such a severe gradient of change. As the spectral composition of light can change with different levels of illuminance it is also possible that visual acuity may be influenced by wavelength.

2.2.2.4 Dark adaptation and scotopic vision

Dark adaptation refers to the recovery of the visual system in darkness or very dim light conditions, following exposure of the eye to brighter illumination (Leibrock et al, 1998). Wells et al (1975) found that the mean dark adaptation curves of the mallard, obtained in a behavioural test, show a distinct break in the absolute threshold sensitivity for the detection of light at 25 minutes, before stabilising at a relatively constant level. Similar tests have shown breaks in the dark adaptation curves of the pigeon and human at 20 minutes and 10 minutes respectively (King-Smith, 1971). These breaks indicate a change in the rate of dark adaptation, and are attributed to the rod adaptation mechanism (scotopic or dim light vision) taking over from that of the cones (photopic or bright light vision). The illuminance thresholds at which this occurs have been reported in different units for the pigeon (0.11 log units) and the mallard (0.15 lux), making comparisons between the species difficult. No data on the dark adaptation of the turkey eye or illuminance thresholds at which this occurs are available in the literature.

Wells et al (1975) suggest that the range of illuminance found during most twilight (10-1.0 lux) and full moon (0.18 lux) conditions would provide illumination in excess of the mallard's photopic visual sensitivity threshold. This means that ducks have eyes with the capacity to function photopically under most levels of illumination that occur during clear moonlit nights as well as in the daytime. How ducks use this ability is not clear, as they are also well adapted to use tactile and taste cues during foraging and can use these exclusively (Martin and Lett, 1985; cited by Jane, 1986). It is possible that these different sensory abilities may be used to various degrees under certain illuminance conditions. For poultry in commercial housing, the scotopic vision of the birds is mainly

of importance only when its influences on other visual abilities such as acuity are considered. Acuity alters in different illuminances, particularly when scotopic vision is invoked. The resolution of the eye is greatly reduced as the outputs from rod cells are pooled over a larger area than cones and therefore the neural sampling of the retinal image is "grainer". Interpretation of movement, as interpreted from flicker sensitivity is also poorer in scotopic conditions as the rods react more slowly than cones (Cornsweet, 1970). These abilities improve with higher illuminance levels as cone photoreceptors (photopic vision) start to respond.

2.2.2.5 Photopic spectral sensitivity

Photopic spectral sensitivity, or colour vision, is the ability of an animal to discriminate different wavelengths of light under conditions of bright illumination in which cone photoreceptors mediate the visual response. Evidence for colour vision in ducks and turkeys comes from psychophysical or behavioural discrimination tests and analysis of the wavelength absorbance properties of visual pigments and oil droplets. In the duck, the behavioural evidence for UV_A vision was reported by Parrish et al (1981) using heart rate conditioning experiments. This study showed ducks to be maximally sensitive to UV_A at $340 < \lambda < 360$ nm. In turkeys, Crescitelli et al (1964) using pigment extraction methods found evidence of just one single cone visual pigment (maximal sensitive to λ=562 nm). Such studies obviously provide an incomplete assessment of the possible colour vision of these species.

However, microspectrophotometry methods have so far provided the most convincing evidence of colour vision in these two species. Hart et al (1999) and Jane and Bowmaker (1988) estimated the spectral sensitivities of turkeys and ducks respectively, by considering the combined effects of the wavelength absorbance properties of the visual pigments, oil droplets and ocular media. This method predicted peaks of sensitivity for the VS (violet-sensitive), SWS (short wavelength-sensitive), MWS (medium wavelength-sensitive) and LWS (long wavelength-sensitive) at 415, 460, 540, and 600 nm, respectively in the duck. These estimates include the observation that the ocular media of the duck eye showed significant absorbency rather than transmission of UV_A wavelengths between $340 < \lambda < 400$ nm. Jane and Bowmaker (1988) proposed that this will result in ducks being relatively insensitive to wavelengths below λ=400 nm. Hart et al (1999) estimated peaks of sensitivity for the single cones of turkeys at 426, 470, 521 and 575 nm. The spectral transmission of the ocular media of the turkey eye

suggests that they have considerable sensitivity to wavelengths in the $315 < \lambda < 400$ nm range, with 50% transmission occurring at λ=358 nm. However, it should be noted that these studies based of microspectrophotometry methods are only able to show the potential for colour vision in ducks and turkey, and are not what the bird consciously perceives.

Numerous studies have attempted to correlate the distribution of retinal oil droplets and their associated visual pigments with the ecology of birds (for reviews see Muntz, 1972; Lythgoe, 1979; Martin, 1985; Hart, 2001a; Hart, 2001b). The distribution of oil droplets across the retina of the duck was described by Jane (1986) as "unremarkable", because the duck was found to possess a uniform distribution of oil droplet types with little variation between the 16 sample areas tested. In the same study, no obvious red or yellow fields were detected, although they exist in the pigeon (Bowmaker, 1977). Red fields are often situated in the dorso-posterior part of the retina (the part responsible for forward and downwards field of vision), and have been associated with the ability to peck at individual food items and discriminate different foliage and berry types (Lythgoe, 1979). An obvious red dorsal field may therefore, not be required by the duck as its food selection is guided by tactile and taste cues rather than visual cues (Martin and Lett, 1985; Martin, 1986). It is suggested that the lack of specialised fields in the retina is a consequence of the generalist lifestyle of the duck and its wide range of habitat usage. Hart et al (1999) do not discuss the distribution of the oil droplets and photoreceptors in the turkey, except to say that it is comparable to that of other Galliformes. Therefore, it is also likely that whilst the overall ratios of different cone types may vary in the turkey retina, there may also be no significant colour oil droplet fields, but this has not been quantified.

The perception of colour brings a number of advantages to a bird, and an increasing number of studies show that colour cues are used by avian species for a range of functions that have biological relevance. Colour vision, including the ability of most birds to perceive UV_A, has been shown to have several roles in the ecology of birds (Derrington, 2002). It enables discrimination between objects and the detection of food items (e.g., plants, seeds, berries) through the reflectance of certain wavelengths (Burkhardt, 1982). Different wavelengths have been shown to be used for signalling communication between conspecifics, such as the visual assessment of a potential mate (Omland, 1996; Jones, 1999; 2001). Since bird plumage tends to reflect UV_A strongly

(Prescott and Wathes, 1999b), this wavelength may have a particular role in this. UV_A may also have a function in avian navigation and orientation, possibly using the strongly polarized UV wavelengths to detect patterns of UV e-vectors in the sky to determine direction, although this has not been shown experimentally (Bennett and Cuthill, 1994).

The structure and functioning of the colour detection system detailed above indicates that ducks and turkeys will have tetrachromatic vision (see Table 2.2), suggesting sensitivity to a broader range of wavelengths than that perceived by trichromatic humans. However, although these studies have predicted the spectral sensitivities of these birds, they only detail what range of wavelengths the eye is capable of detecting, and not how the birds actually perceive different colours. Psychophysical tests also enable the post-retinal processing of colour information to be considered. Knowledge of the perceived spectral sensitivity of ducks and turkeys would provide important information concerning how these birds perceive and interact with their light environment. The implications of this visual ability are important in a number of ways for the rearing of these birds under artificial lighting, and these are discussed further in Chapter 3.

2.2.3 Conclusions on the visual adaptations of ducks and turkeys

The structure of the visual system and the consequent visual abilities of ducks and turkeys suggest that these birds both have visual systems that are adapted for general lifestyles, reflecting the broad range of natural habitats exploited by the progenitor species of these birds. Whilst ducks have a water-based ecology, their visual system does not show the more extensive adaptations for functioning in water as well as air, that are displayed by other aquatic species such as penguins, seabirds and diving ducks (Ischreyt, 1912; cited by Martin, 1985; Lythgoe, 1979; Sivak and Vrablic, 1982). The extent to which they have attained underwater visual capability goes largely with the duration of their underwater periods, and their methods of feeding on the surface or in shallow water. Indeed it is not even clear if ducks open their eyes underwater when foraging, although it is stated by Jane (1986) that they do not. The low illuminance thresholds at which ducks have been shown to attain full dark adaptation (0.15 lux) (Wells et al, 1975), and their rod-dominated retina suggests they may be adapted for vision in dimmer light than other poultry species. The visual system of the turkey, although different to that of the duck in some aspects, also suggests general avian

adaptation to extract visual information from their environments. The differences that have been highlighted above between these two species in their visual systems and consequent visual abilities suggest that ducks and turkeys may respond differently to certain aspects of their light environment. The interactions of these visual abilities and the light environment in commercial housing have some significant effects on poultry, and these are discussed further in section 2.3 with regard to the effects of wavelength and illuminance.

2.3 The effects of wavelength and illuminance on the productivity, health and behaviour of poultry

In many poultry houses the light environment is controlled in terms of light illuminance, source, colour and photo-period. These are often controlled at levels that the progenitors of domestic birds may not have evolved to exploit, and which might prevent poultry using their visual abilities to their full capacity. In such houses, the design of lighting systems is largely determined by production parameters, ease of maintenance and human visual abilities, often with little consideration given to the visual abilities of the birds or the visual information they may require from their environment to perform their natural range of behaviours (see Chapter 4 for a discussion on the characteristics of the light environment in duck and turkey housing). The above review of avian vision has shown this sensory ability to be very important to poultry, as reflected in certain physiological characteristics and the ecology of these birds. Many of the effects of light are mediated by vision (Prescott et al, 2003), particularly those that influence behaviour and production parameters such as feed intake. However, the effects of lighting may also be due to non-visual photoreception, such as light penetration of the skin or through the skull to the pineal gland (Lewis and Morris, 2000).

Lighting is one of the smallest costs involved in the production of poultry meat, but it is also one of the easiest environmental conditions to manipulate. It also can have great influence on the economics of poultry production (Nixey, 1994) through its effects on bird behaviour, health and physiology in ways that interact to affect production (Forbes and Thompson, 2002). Thus, the effects of light on the production parameters in some poultry species have been studied in detail and have been exploited in conventional commercial husbandry systems. Whilst we now have a good understanding of the effects of lighting, especially photoperiod, on reproduction and production (Morris,

1967; Levenick and Leighton, 1988; Cherry, 1993; Lewis et al, 1998; Lewis, 2000) less is known of the involvement of light in the behaviour and health of poultry. The effects of wavelength and illuminance are also less well understood, as research findings are sometimes contradictory, often preventing clear conclusions being drawn. However, it is important to investigate and understand the possible effects of wavelength and illuminance, as they can affect the availability and quality of the visual information a bird extracts from its surroundings, and to a degree its interactions with its environment. Therefore, this section reviews research that has been conducted into the effects these two aspects of lighting have on the productivity, health and behaviour of poultry reared for meat production.

Unfortunately, the majority of research is limited to studies in domestic fowl and turkeys. Whilst there are numerous studies on the behavioural ecology of wild waterfowl, and a more limited amount of literature on factors affecting the production, health and behaviour of domestic ducks, very few have investigated the effects of lighting. Where the effects of light environment are considered, these are restricted to reproduction and egg production (Benoit, 1964; Cherry, 1993; Davis et al, 1993). In the literature there appears to be a scarcity of studies that report the effects of illuminance and wavelength on the productivity, health and behaviour of ducks reared for meat production.

Some difficulties are encountered when reviewing research into the effects of wavelength and illuminance. This is because the effects of wavelength cannot often be separated from the effects of illuminance in many past studies. The wavelength or (spectral composition) of light can alter the perceived illuminance of light, and likewise, as illuminance changes so may the wavelength contribution of some light sources. Different light sources such as incandescent and fluorescent lighting also have distinct wavelength characteristics which alter the perception of their output. Many studies have not controlled for these factors and therefore have mistakenly confounded wavelength and illuminance. Others have attempted control for this by equating the light treatments for illuminance (lux), photon flux (photons m^{-2} s^{-1}), irradiance (W/m^2). However, a recent study has shown that domestic fowl (Prescott and Wathes, 1999a) have a different spectral sensitivity to that of humans, and other studies predict the same for ducks (Jane and Bowmaker, 1988) and turkeys (Hart et al, 1999). The implications of this are that birds may perceive the illuminance from various light sources differently to

humans, even though they appear of equal brightness to human perception (see Chapters 3 and 4). Therefore, despite efforts to equate for illuminance, birds may still perceive illuminance differences between wavelength treatments, including those that contain a UV component, in most of the studies reviewed in this thesis (Morris, 1967; Nuboer et al, 1992; Prescott and Wathes, 1999a; Lewis and Morris, 2000). The measurement of illuminance, as perceived by domestic fowl, in the alternative units, "galluminance" or the "*c*lux", has been proposed by Nuboer et al (1992) and Prescott and Wathes (1999a), respectively to avoid these issues. These use the spectral sensitivity of the fowl in their calculation of illuminance, rather than that of the human. Studies equating wavelength treatments using such units are therefore potentially able to untangle the effects of wavelength and illuminance, and provide evidence of their effects on these birds independent of each other. However, no such units exist for other poultry species such as ducks and turkeys.

2.3.1 The effects of wavelength and illuminance on productivity

A considerable number of studies have been conducted into the effects of all aspects of lighting on the productivity of poultry. Parameters such as growth rates, food conversion efficiency, rates of sexual maturity and egg production have all been investigated. Wavelength effects on sexual maturity have been noted for the fowl (Lewis and Morris, 2000), mallard (Benoit, 1964) and turkeys (Gill and Leighton, 1984). These responses are most likely to be mediated by the differences in penetration of the skull and reception by the pineal gland by different wavelengths of light. Illuminance also affects reproduction and egg production in pullets (Lewis and Morris, 1999). Studies investigating light source and illuminance effects on reproduction and egg production in Pekin ducks (Davis et al, 1993) and geese (Pyrzak et al, 1984) do not consider the wavelength differences between the light sources used at different intensities, raising doubts concerning their conclusions. However, these effects pertain more to breeding birds than those reared for meat production. For the purpose of this discussion, only the effects of wavelength and illuminance on the production parameters most critical to the production of meat birds will be reviewed.

2.3.1.1 Wavelength and growth

The results of some experiments conducted into the growth of fowl and turkeys under different coloured lighting have shown no significant difference in growth rate between

light treatments (Barrott and Pingle, 1951; Smith and Phillips, 1959; Kondra, 1961; Cherry and Barwick, 1962; Schumaier et al, 1968; Proudfoot and Sefton, 1978; Wathes et al, 1982). It should also be noted that these studies used commercial lamps in their trials, which often are not monochromatic in their spectral composition, potentially masking the effects of particular colours of light (Leighton et al, 1989). However, some authors do give detailed accounts of the spectrum of the lamps used, and also recognised in their studies the consequence of equating these lamps using the lux unit for illuminance measurement and perception (Wathes et al, 1982).

In comparison, some studies that compared various narrow-bandwidth coloured lights of the same illuminance (lux) or irradiance (W/m^2), found an effect of wavelength on growth. These show either a trend towards improvement, or a significant increase in the growth of broilers exposed to wavelengths of $450 < \lambda < 560$ nm (blue to green), compared to birds reared in >630 nm (red) or broad spectrum white light (Foss et al, 1972; Wabeck and Skoglund, 1974; Johnson et al, 1982; Rozenboim et al 1999). In turkeys, such trends (Gill and Leighton, 1984) and significantly better growth (Levenick and Leighton, 1988) have been observed in birds reared in narrow-band, blue-filtered lighting compared to red-filtered or white light, at least up to 16-18 weeks of age. After this age, weight gain improved in the latter two treatments of the Levenick and Leighton (1988) study. A possible explanation for this finding of biphasic growth rate relates to the fact that longer wavelengths are more stimulating for sexual maturation than shorter wavelengths. This increased growth coincides with increased levels of sex hormones at this point of the production cycle, and therefore, may not be a direct effect of wavelength on growth (Levenick and Leighton, 1988, Lewis and Morris, 2000). Since many of these studies show similar growth effects for red and white light, but growth under green and blue seems to be improved compared with white light, it has been suggested that growth is suppressed by the longer wavelengths (Foss et al, 1972), rather than enhanced by the shorter wavelengths of blue and green (Lewis and Morris, 2000). As the stimulation of sexual maturation in mallard drakes has also been reported to be greatest under white and red lighting (Benoit, 1964) it may be that similar effects on growth may occur for ducks, although this has not been investigated experimentally.

The provision of supplementary UV lighting (between 0.06 and 0.16 W/m^2 at floor level) to commercial white incandescent light has no significant effect on the growth rate of male turkeys compared with that achieved without UV supplementation. Nor

was any effect found when supplementing white fluorescent light sources (Lewis et al, 2000). The authors conclude that it is unlikely that supplementary UV has any effect on growth, despite the likelihood that their findings in may be the results of a confounding illuminance/wavelength effect, and also subject to the complex interactions that occurred with other enrichment treatments employed in these trials (Lewis et al, 2000). Thus, the effects of UV wavelengths on growth have not been established in the literature.

2.3.1.2 Illuminance and growth

Contrary to the common hypothesis that brighter illuminances reduce growth performance due to increased activity, body weight in broilers is reported to be only marginally depressed at brighter illuminances (Lewis, 2000) or for there to be no response to illuminance (Weaver and Siegel, 1968; Newberry et al, 1988). Similar results have also been noted in male and female turkeys (Lewis et al, 1998; Leighton et al, 1989; Denbow et al, 1990). Wathes et al (1982) found the growth of male broilers to be unaffected by illuminance, but growth in females was found to be progressively depressed at illuminances above 3 lux. Some other studies have also found growth to be affected by illuminance. In broilers, better growth has been reported at 22 lux compared to 66 lux (Shoffner, et al, 1962). Bacon and Touchbarn (1976) also found the same effect at 0.11 lux compared to 11 and 33 lux (incandescent lighting) up to 12 weeks of age, but best growth was observed later at 22 weeks in birds reared under 11 lux. In turkeys, Siopes et al (1983; 1984) found growth to be poorer in birds reared in 1.1 lux compared to 11 lux or higher, whilst better growth has been reported for these birds at 10 lux compared to 700 lux of fluorescent lighting (Yahav et al, 2000). Possible reasons for the contradictory results may be due to the different photoperiods used within and between these studies (Siopes et al, 1983), the different light sources used (Lewis and Morris, 1998), or a lack of control of the wavelength and illuminance interaction, making assessment of the influence of illuminance difficult.

2.3.1.3 Wavelength and feed efficiency

The results of many studies have suggested that feed intake, conversion and thus efficiency are not influenced by wavelength in broilers (Kondra, 1961; Cherry and Barwick, 1962; Wells, 1971; Wabeck and Skoglund, 1974; Wathes et al, 1982; Prayitno, 1994; 1997a). In turkeys, an increase in feed efficiency under red lighting to that found for blue after 16-18 weeks of age is considered to be also due to the increased

levels of sex hormones (Levenick and Leighton, 1988). Despite these contradictory results, Lewis and Morris (2000) suggest that feed intake in general does not seem to be influenced by wavelength, but that as long wavelength (red) light appears to suppress growth under 16 weeks of age in fowl and turkeys, feed conversion should therefore be more efficient under blue and green light than under red lighting.

2.3.1.4 Illuminance and feed efficiency

Studies into the effects of illuminance on feed efficiency in fowl and turkeys also yield contradictory results, possibly for the same reasons given above for the illuminance effects on growth. Some indicate improved feed efficiency under lower illuminances (Hester et al 1987; Yahav et al, 2000), whilst Siopes et al (1984) showed that very low illuminance (1.1 lux) adversely affected feed intake and efficiency, but no effects of the other illuminance treatments used in this study, ranging from 11-220 lux, were found on this parameter. Other studies note no effect of illuminance on feed efficiency in male or female turkeys (Leighton at al, 1989; Denbow, 1990) or broilers (Newberry et al, 1986).

2.3.2 The effects of wavelength and illuminance on mortality

The environmental effects on mortality are important to investigate due to their direct effect on the productivity of flocks and for welfare reasons. Increases in mortality rates can indicate the incidence of disease and behavioural problems, or the failure of animals to cope with an environment (Broom, 1986; Webster, 1994). Due to the lack of literature detailing the effects of lighting in general on mortality in ducks, this discussion is restricted to research conducted on fowl and turkeys.

2.3.2.1 Wavelength and mortality

Several studies have concluded that wavelength does not significantly influence mortality rates in broilers (Wabeck and Skoglund, 1974) or turkeys (Gill and Leighton, 1984; Levenick and Leighton, 1988) when lighting had been equated for illuminance (lux) or irradiance (W/m^2). Similar results have been reported in studies which used coloured commercial lamps in their trials, which were not monochromatic in their spectral composition, with broilers (Cherry and Barwick, 1962; Proudfoot and Sefton, 1978; Wathes et al, 1982) and in fowl and turkeys (Kondra, 1961). In contrast, some researchers do report an effect of wavelength on mortality. In broiler breeders, Cave (1990) observed a lower mortality rate before and after the laying period in birds reared

under green lighting compared to white light, whilst Wells (1971) found mortality to be increased in pullets reared under red incandescent light compared to white.

2.3.2.2 Illuminance and mortality

Data on the mortality rates of poultry reared under different illuminances are also not conclusive. Several studies concluded that illuminance had no significant effect on mortality in broilers (Cherry and Barwick, 1962; Wathes et al, 1982; Newberry et al, 1986). However, contradictory results have been reported by Newberry et al (1988) who found no effects of illuminance on mortality in broilers in one trial but a higher rate to occur in dim light (6 lux) to bright (180 lux) in a second trial. Experimenters found no apparent reasons for this, though they were able to rule out the depression of feed and water intake during brooding and a number of other effects in the experimental design. Siopes et al (1983; 1984) also observed higher mortality under low illuminance (1.1 lux) compared to 11 lux, and attributed this to birds not being able to locate food resources and therefore starving under this light treatment. Other studies found mortality in male turkeys to be higher in those reared under 86.1 lux than the lower illuminance of 10.8 lux, although no reasons for this were given (Leighton et al, 1989).

However, few of the above reports detail the causes of deaths, so mortality and culls may possibly be confused in the data of these studies. If data for mortality and culled birds are combined in some studies then the effects of illuminance on the ability of stockpersons to inspect the birds may also play a role. Under illuminance levels of 1 lux or lower stockpersons may not be able to adequately see birds for inspection, identify signs of disease, differentiate between blood and faecal staining of the plumage, or check the satisfactory functioning of drinkers and feeders (Appleby et al, 1992).

2.3.3 The effects of wavelength and illuminance on health

Aspects of artificial lighting have been implicated in the aetiology of a number of significant health and welfare problems in poultry production. Eye abnormalities probably account for the reports of turkey blindness in some commercial flocks (Ashton et al, 1973), and will obviously have an impact on visual abilities such as accommodation and spatial acuity in birds reared under such conditions. Leg disorders are another health issue of major concern in the poultry industry, both on economic and welfare grounds. Such abnormalities can have great effects on the mobility of birds, and

may cause considerable pain. Whilst both eye and leg abnormalities are also known to be influenced by other factors such as genotype (Kestin et al, 1992; Trolio et al, 1995), the effect of lighting is also a significant factor. This has prompted studies into the various aspects of lighting on these conditions for fowl and turkeys. Leg disorders are reported in duck species, but so far studies have investigated the involvement of genetic factors rather than light conditions (Chapuis et al, 2001).

2.3.3.1 Wavelength and eye abnormalities and visual development

There is no evidence that wavelength affects the development of vision or the occurrence of eye abnormalities in poultry. Instead photoperiod and illuminance are shown in many studies to be the light factors involved in the development of vision and eye abnormalities (see section 2.3.3.2. The effects of illuminance on eye abnormalities and visual development). In support of this, Brenner et al (1983) showed that early colour deprivation using profound changes in the colour balance of lighting in the rearing environment for pigeons did not affect the spectral sensitivity of these birds when later tested. This suggests that colour vision is not affected by the wavelengths which birds are reared under, but does not exclude possible effects on other avian visual abilities.

The use of UV lighting though is often considered to have detrimental effects on the eye and vision. Barrott et al (1951) found that UV_C lighting ($200 < \lambda < 280$ nm) increased the incidence of conjunctivitis in fowl. In contrast, Hogsette et al (1997) found no eye abnormalities in layers constantly exposed to blacklight and blacklight-blue fluorescent tubes ($310 < \lambda < 390$ nm) from insect traps. These studies may indicate that UV_C radiation rather than UV_A has detrimental effects on the eye and thus vision in fowl (Lewis and Morris, 1998).

2.3.3.2 Illuminance and eye abnormalities and visual development

Long photoperiods and illuminance are the two aspects of commercial lighting that have been shown in the literature to change the morphology of the eyes in poultry, leading to abnormal development of vision and even complete or partial blindness (Ashton et al, 1973; Siopes et al, 1984). These abnormalities include bupthalmia (glaucoma), an increased thickness of the choroid layer and corneal flattening. Bupthalmia is an elevated intra-ocular pressure (IOP), which is manifested by the accumulation of fluid, resulting in an enlargement and protrusion of the eye (Shivaprasad, 1999). Bupthalmia

can occur in dim and bright light conditions, as well as under continuous lighting (Oishi and Murakami, 1985) and continuous darkness (Jenkins et al, 1979). The effects of dim light bupthalmia differ to those which are induced by continuous lighting. In bupthalmia caused by continuous lighting, an increase in IOP persists within the eye as the bird ages, whereas in dim light bupthalmia IOP increases up to 4-6 weeks, and then decreases whilst the size of the eye continues to increase. Bright light bupthalmia also develops at a different rate, and IOP varies to that of dim light bupthalmia (Lauber and McGinnis, 1966; Thompson, 2001).

Illuminance has been shown to affect the morphology of turkeys' eyes (Thompson and Forbes, 1999; Thompson, 2001). Turkeys kept under 2 lux had significantly enlarged eyes, determined by their weight and dimensions, as well as other morphological effects, suggesting that dim light bupthalmia occurs at this illuminance compared to 5 or 10 lux. Birds housed under 50 lux in the same study showed some effects indicating the possible development of bright light bupthalmia compared to those reared in 5 or 10 lux. These results were shown to occur independently of photoperiod effects. Other studies in turkey poults have also found that low illuminance (1.1 lux) induces eye abnormalities such as enlargement of the eye and corneal flattening compared to birds reared in 11 lux (Siopes et al, 1984). In prolonged periods of dim lighting retinal detachments have also been recorded in fowl (Harrison and McGinnis, 1967; cited by Manser, 1996). The incidence of dim or bright light bupthalmia in ducks is not described in the literature. However, for unknown reasons domestic ducks appear not to be prone to bupthalmia induced by continuous lighting, instead developing cataracts (Lauber, 1987).

These changes in the eye are likely to affect visual ability of poultry through causing refractive errors to occur. In chicks with dark-induced eye abnormalities, the sclera, choroid, retina and retinal layers were not as thick as those in birds reared under conventional light management, and the corneas of such birds exhibited a reduction in curvature and thickness (Jenkins et al, 1979). In turkeys reared in dim light conditions of 2 lux, that induced dim light bupthalmia, similar morphological changes were also observed, including an increased depth/axial length of the eye (Thompson, 2001). Lauber et al (1970) suggest that this enlargement of the eye is likely to lead to a flattening of the cornea which will reduce its refractive power, possibly resulting in myopia (Harrison et al, 1968; cited by Thompson, 2001). Poultry reared under light

conditions that can result in these abnormalities may therefore have impaired accommodation and spatial acuity, and may be less able to extract visual information from their environment (Lauber, 1987) (see section 2.2.2.1 Accommodation and 2.2.2.3 Spatial acuity). This could negatively affect the welfare of poultry if the birds fail to identify co-specifics or their intent, or the birds are unable to orientate themselves within their environment. Additionally, increased IOP in humans (known as glaucoma) is known to cause discomfort and pain. Whilst behavioural observations of birds with comparative eye conditions are sparse, it is not unreasonable to presume that severe bupthalmia could also cause discomfort and pain in affected poultry.

2.3.3.3 Wavelength and leg disorders

Wavelength has been shown to affect the incidence of leg disorders by Prayitno et al (1997b). When birds were reared under red light (8.6 x 10^{23} photons m^{-2} s^{-1}) early on in life (1-16 days) it was shown to reduce lameness in comparison to blue light (0.015 x 10^{23} photons m^{-2} s^{-1}) through increasing walking and stretching behaviour. However, in the same studies, bone strength was reduced when birds were exposed to red light later in their production cycle (days 17-32).

2.3.3.4 Illuminance and leg disorders

In comparison to the limited information in the literature on the impact of light wavelength on poultry leg disorders, considerably more studies have been conducted investigating the effects of photoperiod (Buckland et al, 1976; Hester et al, 1985; Classen and Riddel, 1989; Clarke et al, 1993) and illuminance. Haye and Simons (1978) suggested that the incidence of leg problems and walking difficulties increased as birds exercised less. Therefore, the commonly reported inactivity of meat birds housed under commercial illuminance levels (Appleby et al, 1992) has been linked to the occurrence of leg disorders (Manser, 1996). This is supported by the findings of experimental studies. Broilers housed under 6 lux were found to have a higher incidence of leg abnormalities than those reared at 180 lux (Newberry et al, 1988) and this was attributed to the lower levels of activity observed in the 6 lux treatment. Similar findings have been reported for turkeys, showing that the incidence of tibial dyschrondroplasia (a build up of cartilage causing the tibia bone to bend and splay in severe cases) was higher in birds kept in 2.5 lux compared to 20 lux (Hester et al, 1985).

2.3.4 The effects of wavelength and illuminance on behaviour

Compared to the number of studies investigating the effects of wavelength and illuminance on poultry production parameters, fewer studies report the behavioural responses of poultry to these light conditions. This is despite the fact that certain behaviours such as feeding, feather pecking and cannibalism can affect productivity and welfare (Appleby et al, 1992). In addition, relatively little is known about the involvement of avian visual abilities in these key behaviours (Prescott et al, 2003); although these will undoubtedly exert influence on behaviour as many behavioural responses to light are mediated by vision (Lewis and Morris, 2000; Prescott et al, 2003). It is important to make scientific assessments of these behavioural responses, and consider them alongside production and welfare parameters so they can be used to evaluate whether poultry can adapt to changes in production systems, made with the aim of improving efficiency and productivity without compromising welfare (Siegel, 1984). Since we have no direct knowledge of avian subjective emotions or the degree to which they may suffer under particular conditions, we rely on such studies to provide indirect evidence of the birds' physiological and psychological state to use as possible indicators of poultry welfare (Dawkins, 1976; 1980).

2.3.4.1 Wavelength and activity

One of the most noted effects of different coloured light on poultry behaviour is that on general activity and movement. The term "activity" is used in some studies simply to distinguish between when birds are resting or sleeping and when birds are performing a range of behaviours that require them to move; others define "activity" as locomotion. Despite this, many studies generally conclude that wavelength influences activity levels in poultry, however they are defined. Levenick and Leighton (1988) have shown that turkeys are less active in blue light compared to red or white of the same illuminance (lux). Similar results were found for broilers (Prayitno et al, 1997a) with birds reared in red light being more active than those reared in blue or green. However, in these studies, broilers were also observed to sleep more in red light, whilst those reared under blue or green spent more time inactive through sitting and resting on the litter (Prayitno et al, 1997a). As well as increased activity, Prayitno et al (1997a) also observed more floor-directed pecking under red light compared with the other wavelength treatments. Whilst the above studies equated wavelength treatments to the same illuminance (lux) level and photon flux (photons m^{-2} s^{-1}) respectively, the results correspond to the findings of a

study that used wavelength treatments equated using the *c*lux unit. Perkins (2001) showed in an open-field test that blue light reduced activity in broilers more than white or red light that was isoluminant with respect to the birds' spectral sensitivity.

Studies investigating the effects of supplementary UV_A light on general activity have shown little effect of treatment. No significant effect of UV_A ($300 < \lambda < 400$ nm) on exploratory behaviour was found in domestic fowl chicks (Maddocks et al, 2001). Non-significant trends were noted for more ground scratching and environmental pecking by birds reared in light with supplementary UV_A ($300 < \lambda < 400$ nm) compared to fluorescent lighting without UV_A, but which was equalised for brightness in terms of the overall quantal flux ($Q.d\lambda$). This surprised the authors as they had hypothesised that the UV_A reflectance of the substrate (shown by Prescott and Wathes, 1999b) would increase the attractiveness of the wood-shavings litter to the birds and invite more pecking (Maddocks et al, 2001). Jones et al (1999; 2001) did find an effect, with locomotion in male broiler breeders to be significantly increased in fluorescent lighting supplemented with UV_A compared to conventional fluorescent lighting of equal *c*lux. However, the use of white commercial lamps in these studies, which provide a broad range of other wavelengths that may mask the effects, if any, of the UV_A, or it may be simply that UV_A is utilized by birds for other behaviours.

2.3.4.2 Illuminance and activity

It is commonly thought that reducing illuminance levels results in a decrease of activity and exploratory behaviour in poultry, and anecdotal observations support this (Deaton et al, 1976). Supporting experimental evidence is also in abundance. Both physical activity and energy expenditure in fowl were found to increase progressively in response to a range of illuminances between 1 and 120 lux (Boshouwers and Nicaise, 1987). In another comparison, broilers reared in brightly lit pens (180 lux) were found to be more active than those in dimly lit pens (6 lux) (Newberry et al, 1988). Thompson (2001) found a similar effect on activity in turkeys; birds housed under 2 or 5 lux were significantly less active and displayed very little exploratory behaviour compared with those reared under either 10 or 50 lux. General activity level in laying hens was also greater in birds reared in bright illuminance (55 to 80 lux) than in birds reared under dim illuminance (17 to 22 lux) (Hughes and Black, 1974). Thus, illuminance appears to have a significant positive relationship with general activity and energy expenditure in fowl (Proudfoot and Sefton, 1978). Preference tests in fowl (Davis et al, 1999) also

show that there is a distinct relationship between illuminance and activity, and that this changes with age. Fowl prefer to perform a number of active behaviours including locomotion and litter-directed pecking in 200 lux compared to 6, 20 and 60 lux at 2 weeks of age. However, the initial preference for bright light weakens as the birds age, and they begin to prefer to rest and perch in dim light (6 lux) by 6 weeks of age. This suggests that fowl have a preference to perform different behaviours in different illuminances (see Chapter 5 The preference of growing ducklings and turkey poults for illuminance).

2.3.4.3 Wavelength and feeding and drinking

In their review of the effects of coloured light on poultry, Lewis and Morris (2000) conclude that feed intake does not seem to be influenced by wavelength. However, this is largely based on experiments that assess the amount of feed consumed by birds, rather than observations of the frequency and duration of feeding and drinking behaviour. Although the former allows the assessment of feed efficiency, this parameter does not tell us much about the role of wavelength in feeding behaviour. Such information in the literature is scant. Prayitno et al (1997a) found there was no overall effect of wavelength on the time spent feeding by broiler fowl, but an interaction with the sex of the bird was demonstrated. The time spent feeding by male birds increased in green and blue lighting compared to red and white, whilst in females the time spent feeding increased in white and to a lesser extent red light. A similar interaction was found for drinking behaviour, with males spending more time drinking in blue light than in the other wavelength treatments, and females spending more time drinking in the white light. It is suggested by the authors that these results are due to male birds directing their increased motivation for activity in white and red light towards interactive behaviour with other birds and the environment rather than feeding and drinking (Prayitno et al, 1997a).

There is abundant literature on the possible uses of UV cues by wild birds and its role in foraging and feeding behaviour (Burkhardt, 1982; Bennett and Cuthill, 1994; Church et al, 2001; Cuthill et al, 2000). In natural environments illuminated with daylight the use of such cues has been clearly demonstrated (Viitala et al, 1995; Siitari et al, 1999; Church et al, 1998). However, in many commercial light environments with their lack of UV_A radiation such cues will not be transmitted and thus lost. Commercial poultry food has been shown to reflect UV_A strongly (Prescott and Wathes, 1999b), but whether

the loss of such visual cues affects feeding in fowl, turkeys or ducks is unknown. Martin and Lett (1985; cited by Jane 1986) have provided behavioural evidence that ducks do not require visual cues such as colour for feeding, and are able to rely on tactile and taste cues alone to locate and select food. However, this does not mean that these birds do not use such cues when they are available. Indeed ducklings have been shown to prefer green and yellow-green coloured food, over red or blue (Hess, 1956; cited by Reiter, 1997).

2.3.4.4 Illuminance and feeding and drinking

Common commercial practice for poultry rearing is for constant lighting of a relatively bright illuminance to be provided for the first few days following bird placement to allow birds to learn the location of food and water within the house, then to reduce illuminance for the rest of the rearing period. Locating, selecting and manipulating food prior to ingestion are behaviours highly dependent on vision for most birds. Thus, studies have attempted to assess the illuminance levels required or preferred for these behaviours. Preference studies in fowl and turkeys have also shown that these birds prefer to feed in brighter illuminances. Davis et al (1999) found that fowl prefer to feed and drink in 200 lux rather than 6, 20 or 60 lux, whilst Sherwin (1998) showed that turkeys spent significantly less time feeding in <1 lux compared to 5, 10, or 25 lux, regardless of the illuminance in which they were reared (4 or 12 lux). The motivation of poultry to feed and drink in different illuminance levels has also been assessed by Prescott and Wathes (2002). Fowl were prepared to work approximately 2.3 times harder to access food illuminated by 200 lux than that by <1 lux. Whilst these birds were less willing to eat in dim light (<1 lux), illuminance level did not affect the amount of feed consumed per peck, or the number of pecks made. However, the overall amount consumed was more in the brightest light (200 lux) and there was also a trend for birds to use a lower peck force when feeding in the dimmest illuminance (<1 lux) (Prescott and Wathes, 2002).

From the above studies it may be concluded that fowl and turkeys prefer to eat in brighter illuminance as the process of eating for these birds is normally guided by vision. These results may also reflect the positive relationship of increasing illuminance on spatial acuity (Schlaer, 1937; cited by Kristensen et al, 2002). That fowl, and probably turkeys too given the position of their eyes, are visually guided in their feeding behaviour is also implied by the assessment of their visual fields (see section 2.2.2.2

Visual fields). The visual fields of Galliformes are indicative of species that feed by visual guidance of the bill towards individual objects. This is not the case for mallard, whose visual field suggests that they do not need to monitor the position of their bill when feeding. This, combined with their scotopic visual sensitivity, rod-based retina (Wells et al, 1975) and nocturnal feeding habits in the wild (McNeil et al, 1992), suggests that ducks may be not as dependent on brighter illuminance levels for feeding and drinking as other poultry species. However, this does not mean that they would not show a preference or be unmotivated for feeding and drinking under certain illuminance levels.

2.3.4.5 Wavelength and preening

There are no investigations in the literature which detail the effects of various wavelengths of light on the preening behaviour of poultry.

2.3.4.6 Illuminance and preening

Preening behaviour was observed by Kristensen et al (2003) to be influenced by illuminance. Broilers reared in 100 *c*lux at six weeks of age showed higher levels of preening than those in 5 *c*lux. These illuminance effects were found, irrespective of the light sources used; either warm-white fluorescent light or biolux (a fluorescent daylight stimulant) equated for illuminance using the *c*lux unit. This is in contrast to the findings of Thompson (2001) who observed in turkeys a higher frequency of preening in 2 lux compared to 5, 10 or 50 lux.

2.3.4.7 Wavelength and fear

Within the poultry industry, there is a belief that blue coloured light is more calming and reduces fearfulness in birds, and it has been routinely used during the depopulation of broiler fowl houses partly for this reason (Cook, 2001, personal communication; cited by Perkins, 2001). Until recently, this claim was unsubstantiated, as previous studies had confounded wavelength and illuminance effects (Levenick and Leighton, 1988; Prayitno, 1997a). The observations of less fearfulness in these studies are also debatable, and it is possible the birds may have been less active and thus appeared less fearful. However, Perkins (2001) monitoring the heart rates of birds, showed that blue light reduces fear in broilers more effectively than white or red light that is equated for illuminance using the *c*lux unit.

2.3.4.8 *Illuminance and fear*

There is evidence that laying hens housed at low illuminances (17 to 22 lux) are more fearful, showing a strong avoidance of novel objects, compared to birds housed at higher illuminances (55 to 80 lux) (Hughes and Black, 1974). This is in contrast to the findings of Perkins (2001) who reports an effect of illuminance on the performance of strong avoidance behaviour in broilers to an approaching human. Strong avoidance behaviours occurred sooner in bright red and blue light (20 *c*lux) than in dim red and blue (5 *c*lux). These results may well be due to the positive relationship of increasing illuminance on spatial acuity (Schlaer, 1937; cited by Kristensen et al, 2002). This, combined with the effects of wavelength on fear detailed above (section 2.3.4.7 The effects of wavelength on fear), suggests that a combination of blue light at low illuminances may have benefits for the welfare of poultry during depopulation to reduce fear reactions.

2.3.4.9 *Wavelength and aggression and social interaction*

Several studies have been made into the effects of lighting on aggression in poultry. Research into such behaviour has observed more aggression in broilers illuminated by red lighting than in birds reared under white, green and blue light equated for photon flux (photons m^{-2} s^{-1}) (Prayitno et al, 1997a; 1997b). It is surmised by the authors that this may be due to the red light appearing brighter to the birds, leading to greater activity. This may explain why some poultry farmers believe that there is more aggression under incandescent than under fluorescent lighting, as there is a higher proportion of red wavelengths in white incandescent light (70%) compared to fluorescent light (8-10%) (Lewis and Morris, 2000).

Most studies which have investigated the use of coloured light in social interaction have studied its influence on mating behaviour, or concentrated on injurious pecking (see section 2.3.4.11 The effects of wavelength on injurious pecking). Whilst several studies have clearly shown UV_A to be clearly implicated in mate choice and mating behaviour of birds (Bennett et al, 1996; Bennett et al, 1997) including fowl (Jones et al, 1999; 2001), these effects pertain more to breeding birds than to meat production. However, it has been suggested that UV_A may also play a role in other social interactions. Research has shown that the feathers of domestic fowl (Prescott and Wathes, 1999b) strongly reflect UV_A wavelengths between $300 < \lambda < 400$nm; although tail and wing feathers reflect less than breast and neck feathers. Sherwin and Devereux (1999) found markings

in the plumage of turkeys to be visible under UV light, that are not seen when the birds are viewed by humans under conventional fluorescent and incandescent lighting. It is surmised that these areas may appear dark and "unnatural" to the birds in commercial lighting, and so may prevent social recognition of conspecifics, visual assessment before agonist interactions and make the areas more attractive for injurious pecking (Sherwin and Devereux, 1999; Prescott and Wathes, 1999b).

2.3.4.10 Illuminance and aggression and social interaction

It is generally considered that increases in illuminance increase the occurrence of aggression, although this belief may stem mainly from evidence of the effects of illuminance on injurious pecking, which is now regarded as a distinctly different behaviour, commonly considered to be re-directed foraging or preening behaviour (Kjaer and Vestergaard, 1998; Sherwin and Kelland, 1998). In one study more aggressive behaviour was observed among male turkeys aged 56 to 168 days when they were kept in 86.1 lux than those in 10.8 lux, although the incidence of aggressive behaviour in this study was reported as low in both groups (Leighton et al, 1989). However, the relationship between illuminance and aggressive behaviour in fowl and turkeys is not entirely substantiated. This is partially due to aggression and injurious pecking being classified together in some studies, and most of these detail the effects of illuminance on injurious pecking rather than on aggressive interactions (see section 2.3.4.12).

Studies into the effects of social interactions other than injurious pecking and aggression are few. However, D'eath and Stone (1999) indicated in their study that recognition of familiar from unfamiliar laying hens based on aggressive interactions and preference to feed alongside another bird was possible in bright white light (77 lux) but not in dim white light (5.5 lux). Thus, social interactions in poultry may be reduced or prevented if illuminance levels are too low to allow the transmission of visual social cues by reducing the birds' spatial acuity or their ability to discriminate colours. The effect of low illuminances on eye development may also affect social interactions.

2.3.4.11 Wavelength and injurious pecking

Domestic poultry kept under commercial conditions often perform injurious pecking (feather pecking, head pecking and cannibalism) which can lead to death or require birds to be culled (Hughes and Grigor, 1996; Moinard et al, 2001). These behaviours are

of considerable welfare and economic concern and beak trimming is often used to lower the impact of such behaviours. Some breeds of duck have also been reported to feather peck, particularly muscovy ducks and their hybrids, but these birds are a different species to the commercial pekin type meat ducks that originate from the mallard (Klemm et al, 1993). Feather pecking and abrasion does occur in commercial pekin ducks (Wilson, 2000, personal communication), but is not considered as important an issue as in fowl and turkey production due to the much lower frequency at which it occurs.

Schumaier et al (1968) found that feather pecking and cannibalism in pullets are reduced in red fluorescent lighting compared to green or white light. However, this study made no attempt to equate the coloured light treatments for illuminance and the illuminances used are not stated. Red coloured lighting though, is sometimes used commercially to curb outbreaks of injurious pecking. The rationale for this usage is that birds will be less able to see blood or bleeding wounds in this colour of light (Appleby et al, 1992). However, Wells (1971) suggested that the reduction of this behaviour with the application of red filters may be simply due to the resulting reduction in illuminance.

Research has shown that supplementary UV_A with either white incandescent or fluorescent lighting (each at 5 lux), combined with visual barriers and added straw enrichments minimised the incidence of injurious pecking in male turkeys reared in small groups (Lewis et al, 2000; Perry, 2003). However, the findings in this study may be the results of a confounding illuminance/wavelength effect, and also the complex interactions that were found to occur between the enrichment treatments employed in these trials. In a further study, Moinard et al (2001) showed that supplementing fluorescent lighting (5 and 10 lux) with UV_A, visual barriers and added straw enrichments reduced tail and wing injuries through pecking compared to white incandescent of the same illuminance (lux). This study may also be subject to the same limitations as that of Lewis et al (2000). However, whilst the independent effects of UV_A wavelengths on injurious pecking are not verified in these studies, its use in combination with commercial lighting sources, illuminances and with other forms of enrichment has been shown to have some positive effect. Thus the presence or absence of UV_A may be an important factor in the development of these behaviours, but further research is required.

2.3.4.12 *Illuminance and injurious pecking*

Illuminance has been identified as a major factor affecting the incidence of feather pecking in poultry (Hughes and Duncan, 1972). This relationship has been reported in numerous studies with fowl (Bacon and Touchbarn, 1972; Hughes and Duncan, 1972; Kjaer and Vestergaard, 1998), turkeys (Hester et al, 1987; Leighton et al, 1989; Denbow et al, 1990; Moinard et al, 2001) and pheasants (Kjaer, 1997) and all found more injurious pecking in a range of brighter illuminance levels in comparison to dimmer environments. These increases in injurious pecking with artificial illuminance are in contrast to the reports that non-beak trimmed poultry reared in daylight do not routinely experience problems with injurious pecking. It is proposed by Lewis (2000) that the spectral composition of daylight, with its UV_A component, may be an important factor in this (see section 2.3.4.11). Whereas these undesirable behaviours can be curtailed by the provision of dim lighting (Classen et al, 1994), it does not necessarily follow that bright illuminances were the prime cause. Many other environmental, management and genetic factors have also been implicated in the development of these behaviours, whose causes are not fully understood. These studies also show that the illuminances used to prevent injurious pecking are at variance to the preferences of fowl (Davis et al, 1999) and turkeys (Sherwin, 1998) for various active behaviours, which may compromise their welfare in this respect. It is therefore important to investigate other methods of reducing injurious pecking in poultry.

2.4 Assessing the need for light and the lighting recommendations for domestic ducks and turkeys

The anatomy of the duck and turkey eye retains the properties and characteristics of their progenitor species, and light and vision have been shown to be important in many aspects of these birds' life. In natural habitats birds would require the ability to extract the visual information necessary to locate and select food resources, navigate, recognise their territory, detect predators, identify co-specifics and potential mates and for behaviours necessary for maintaining the dominance hierarchies of groups of birds. However, the light characteristics and the visual environment to which wild mallard and turkeys are best adapted may no longer apply to domesticated birds. Under certain commercial light conditions visual cues relating to the above may not be readily transmitted. It has also been suggested (Prescott et al, 2003) that the relative importance of this information changes when poultry are intensively housed in very large flocks, as

domestic birds may require visual information of a different context to that of wild birds. For example, recognition of a fellow bird's intent may be more useful than its individual identity. Whilst it is therefore important that the visual abilities of ducks and turkeys and the development of their visual system are not impeded by the application of inappropriate lighting, either in terms of duration (photoperiod), spectral composition or illuminance, this does not necessarily require the recreation of the natural light environment in a poultry house. Instead lighting for poultry should be based on the identification and inclusion of lighting criteria considered to be important in enabling domestic birds to assess their environment adequately, and perform a repertoire of visually mediated behaviours deemed key to their welfare without compromising other aspects of bird health or production.

Unfortunately, assessing the requirements of poultry for aspects of lighting such as wavelength and illuminance is not always straightforward. As the above review of research into the effects of wavelength and illuminance on poultry demonstrates, there are few clear indications as to the spectral quality of lighting and illuminance required by poultry. The optimal light environments for domestic ducks and turkeys may not be predicted by looking solely at their visual ecology in the wild, although it does give an indication of the ability of these birds to adapt visually. Ducks and turkeys may have visual systems able to function under a range of light conditions, or they may be able to compensate to different degrees for poor visual function in sub-optimal conditions by reliance on other sensory input. Neither is it entirely appropriate to extrapolate the results of research from one species to another, as subtle differences in their visual system and abilities may results in different responses to light conditions. This review therefore, shows the importance of identifying species-specific needs, preferences and motivations for light wavelength and illuminance rather than implying and imposing conditions based on human perception and preference. Some work into the light preferences of different poultry species has briefly been described above, and it is a very important first step in the assessment of optimal conditions for animals. Chapter 5 will detail further literature investigating the preferences of poultry for light source, wavelength and illuminance.

Despite the range of confounded and often contradictory scientific information available, there is evidence that both the colour of light and its level of brightness can independently influence some poultry species in a wide variety of ways. Based on this

and other research into photoperiods a number of welfare, legislative and retailer organisations have published guidelines and recommendations on the provision of lighting for a number of poultry species including ducks and turkeys. Details of some of the most widely known recommendations and welfare standards that define lighting parameters for ducks and turkeys are given in Table 2.3. The RSPCA Welfare Standards (1999a; 1999b) are reflected in the guidelines of other welfare organisations in many countries around the world, whilst FAWC's (1995) recommendations are presented as advice to the appropriate UK government ministers and as interim measures pending further research. The standards of supermarket retailers such as Marks and Spencer's (1987a; 1987b), whose codes of practice are summarised here, have a large influence on the way poultry are kept for food production.

There is clearly a requirement for these recommendations and guidelines, and they represent the current understanding of the effects of light on the behaviour, health, welfare and productivity of poultry. However, more information is required on which to base future revisions of these guidelines that satisfy both welfare and economic concerns. If we require that poultry are housed under environmentally controlled, intensive housing with artificial lighting for production reasons, then further experimental research is needed. This is acknowledged by the organisations given in Table 2.3, and others (Manser, 1996; Prescott et al, 2003) have also highlighted areas which require further investigation. These include research into the preferences and motivation of poultry for illuminance and levels required for different activities, the standardisation of light measurement and adequately detailed description of light environments for these birds.

In order to make future recommendations on aspects of the light environment in poultry houses that satisfy both welfare and production concerns, an integrated knowledge of the physical environment and some fundamental aspects of poultry vision are initially required. To enable the above guidelines and recommendations to achieve their aims, it is imperative that a standardised method of measuring illuminance in duck and turkey housing is adopted and light environments are adequately described in all aspects (photoperiod, light source, and illuminance). Then research considering such findings will be better able to explain the responses and interactions of poultry to their visual environment.

Table 2.3 Regulations and guidelines concerning lighting for domestic ducks and turkeys.

Source	Species	Minimum Illuminance	Photoperiod	Source	Dawn/ Dusk Dimming	Comments
Council of Europe	Ducks [a]	Sufficient to allow ducks to see each other, to be seen clearly, to investigate their surroundings visually and show normal levels of activity.	Sufficient dark period ~8 hrs, uninterrupted.	Natural daylight, as far as practicable.	Yes.	Where natural light is admitted, it should provide an even light distribution.
	Turkeys [b]	10 lux. Reduction in illuminance may be used if significant injurious pecking occurs.	Sufficient dark period ~8 hrs, no less than 4 hrs.	Natural daylight, as far as practicable.	Yes.	Where natural light is admitted, it should provide an even light distribution. Illuminance to be measured in 3 planes at right angles to each other, at bird eye level.
DEFRA	Ducks [c]	Level to enable all birds to be seen clearly when inspected.	A period of reduced light illuminance in each 24 hrs.	Natural or artificial.		Dimmers should be used to avoid sudden changes in illuminance.
	Turkeys [d]	Level to enable all birds to be seen clearly when inspected.	At least 8 hrs of light, with a period of darkness each 24 hrs.			
FAWC	Turkeys [e] (meat)	25 lux for first few days of brooding. Thereafter, 5 lux. Reduction in illuminance may be used in the event of aggression.	No continuous light after first few days of life. Reduce gradually to give 8 hrs darkness.			Illuminance to be measured on a horizontal plane at bird eye level.

Table 2.3 (cont.) Regulations and guidelines concerning lighting for domestic ducks and turkeys, continued.

Source	Species	Minimum Illuminance	Photoperiod	Source	Dawn/ Dusk Dimming	Comments
RSPCA Welfare Standards (Freedom Food)	Ducks [f]	20 lux	8 hrs light. Min. 6 hrs darkness in each 24 hrs.	Natural or artificial.	Yes	Records of lighting patterns must be kept, recorded automatically where possible. Photoperiod need not apply to first and last three days of rearing.
RSPCA Welfare Standards (Freedom Food)	Turkeys [g]	20 lux	8 hrs light. Min. 6 hrs darkness in each 24 hrs.	Natural or artificial.	Yes	Records of lighting patterns must be kept, recorded automatically where possible. Photoperiod need not apply to first and last three days of rearing.
Marks and Spencer Select Farm Scheme	Ducks [h]	Level to enable ducks to express natural behaviour and movement and to be seen clearly when inspected.	Min. of 1 hr darkness in each 24 hrs.			Artificial lighting should be uniformly located throughout the house and monitored on a regular basis.
Marks and Spencer Select Farm Scheme	Turkeys [i]	5 lux. Reduction in illuminance may be used in the event of aggression, and raised once aggression is controlled.	Min. of 8 hrs darkness in each 24 hrs.			Illuminance level should be measured at bird head height. It should be uniform throughout the house and monitored on a regular basis.

[a]Council of Europe, 1999; [b]Council of Europe, 2001; [c]MAFF, 1987a; [d]MAFF, 1987b; [e]FAWC, 1995; [f]RSPCA, 1999a; [g]RSPCA, 1999b; [h]Marks and Spencers, 1997a; [i]Marks and Spencers, 1997b.

2.5 Study aims and objectives

The above review highlights that there are requirements that are currently not met for accurately describing and measuring the light environment as experienced by poultry other than domestic fowl, both commercially and experimentally. The measurement of light environments in poultry housing is a fundamental issue that undermines both research into lighting, and the practical application of the recommendations based on such information (Prescott et al, 2003). In the past, the light environments or treatments used in numerous experiments have often been only partially or inaccurately described with regard to light source, photoperiod, wavelength, illuminance and the methods used to measure these aspects of lighting. This is due to a lack of standardisation for the practical quantification of light in poultry housing (see Chapter 4). Studies investigating the effects of light wavelength and illuminance also need to avoid confounding these two variables by equating light sources and particular wavelength treatments according to the spectral sensitivity of these birds. Whilst the measurement of illuminance as perceived by domestic fowl, in the alternative units galluminance (Nuboer et al, 1992) and *c*lux (Prescott and Wathes, 1999a) and has been proposed to avoid this (section 2.3), no such units exist for other poultry species. Thus, as the perceived spectral sensitivities of these species are currently unknown and only predicted (Jane and Bowmaker, 1988; Hart et al, 1999), illuminance and wavelength from different light sources continues to be inappropriately measured and described in terms of how it is perceived by ducks and turkeys.

With these issues in mind, the overall aim of this project was to investigate various aspects of illuminance, as perceived by domestic ducks and turkeys. It was hypothesised that as these two species have different ecological backgrounds and some subtle differences in the structure of their visual systems and visual abilities, that they may perceive illuminance and the colour of light differently, and possibly have differing requirements for illuminance when reared commercially. To investigate this, an experiment was conducted to assess the perceived spectral sensitivity of domestic ducks and turkeys using a behavioural test. Following this the lighting conditions and practices within commercial duck and turkey housing were surveyed, including the measurement of the spectral power distributions and illuminance levels of light sources commonly used for the rearing of these species. The results of these two studies were then used to estimate the illuminance perceived by ducks and turkeys for the light sources used in

commercial houses. As an initial first step to help determine a better understanding of the behavioural requirements of these birds for illuminance, a further study was then made to investigate the preferences of growing ducklings and turkey poults for different illuminances in relation to their age and behaviour.

Chapter 3:

The Spectral Sensitivity of Domestic Ducks and Turkeys

3.1 Introduction

The visual systems of poultry species are substantially different to that of humans, particularly with regard to their photopic colour vision (see Chapter 2). In domestic fowl, ducks and turkeys, four visual pigments associated with the single cone cells responsible for photopic colour vision have been identified (see Chapter 2, Table 2.2). These pigments are found in particular combinations with one of five types of coloured oil droplets, which filter incident light before it reaches the visual pigments (see Chapter 2, Table 2.1). This is in contrast to humans that only possess three types of single cone, without any oil droplets, and are thus considered to be trichromatic (Dartnell et al, 1983). In addition, the cornea, lens and humours of the eye in these poultry species allows the transmission of UV_A wavelengths to some degree (Govardovskii and Zueva, 1977; Jane and Bowmaker, 1988; Hart et al, 1999), whereas in humans the lens does not transmit UV_A light (Burian and Ziv, 1959; Geeraet and Berry, 1968). These anatomical differences imply that poultry perceive colour in a very different way to humans, and there is further experimental evidence to support this. The spectral sensitivity curves derived for domestic fowl by Wortel et al (1987), using electrophysiological tests, and by Prescott and Wathes (1999a), using a behavioural test show this species to be sensitive to a different spectral range than humans: the relative response of fowl is broader in its extent than that of humans, extending into the UV_A range as low as λ=360 nm.

With regard to domestic ducks and turkeys it has not been confirmed that their perceived spectral sensitivity is different to that of humans. However, microspectrophotometric data implies that for ducks and turkeys this will indeed be the case. The estimated spectral sensitivity of the single cones in the duck suggests peak absorptions (λ_{max}) at 415, 460, 540 and 600 nm (Jane and Bowmaker, 1988), and approximately 420, 470, 540 and 580 nm in the turkey (Hart et al, 1999) (see section 2.2.2.5 Photopic spectral sensitivity). Further, the results of these studies suggest that there will also be a difference between turkeys and ducks in their ability to perceive UV_A wavelengths. Jane and Bowmaker (1988) found that the cornea, lens and humours

of ducks absorbed rather than transmitted short wavelengths ($340 < \lambda < 400$ nm), with 50% transmission occurring at λ=370 nm and falling to 1% transmission at λ=340 nm. The authors predicted that this will reduce sensitivity at wavelengths below λ=400 nm, resulting in the duck being relatively insensitive to ultraviolet light. In comparison, these ocular media structures in turkeys significantly transmit UV_A between $315 < \lambda < 400$ nm, with 50% transmission occurring at λ=358 nm (Hart et al, 1999). However, this prediction of reduced UV_A sensitivity in the duck does not correlate with the high sensitivity of mallards to UV_A light reported by Parrish et al (1981), using heart-rate conditioning experiments. These findings indicated that the mallard responds maximally to ultraviolet in the $340 < \lambda < 360$ nm range, suggesting greater transmission of UV_A wavelengths within the duck eye than reported by Jane and Bowmaker (1988). Thus, further studies are required to determine the perceived rather than inferred spectral sensitivity of the duck and turkey, including sensitivity in the UV_A range.

There are a number of reasons why knowledge of the perceived spectral sensitivity of these birds is of practical importance. The spectral sensitivity of an animal has strong implications for the measurement of illuminance, which is traditionally measured in the unit lux, using light meters. As these meters are calibrated with reference to the CIE standard human photopic spectral sensitivity curve (CIE, 1983) their measurements are only valid for those animals with a spectral sensitivity similar to that of humans (Nuboer et al, 1992). However, the spectral sensitivity of the domestic fowl has been shown to be more sensitive and broader in its extent to that of humans, particularly between $400 < \lambda < 480$ nm and between $580 < \lambda < 700$ nm (Prescott and Wathes, 1999a), which renders the lux unit inaccurate for measuring and describing the light environment for these birds. Therefore, measurements made within poultry houses, where the light source is the same type throughout the building, may be inaccurate, as the illuminance perceived by fowl may be different to that perceived by a human. Use of the lux unit could underestimate the contribution to the illuminance perceived by fowl of the wavelengths which they are more sensitive to than humans (Lewis and Morris, 2000).

Another implication for the measurement of illuminance concerns the comparison of illuminance measurements between houses lit with different light sources, such as fluorescent and/or incandescent luminaires, as these sources have very different spectral power distributions (Prescott and Wathes, 1999b). Due to their spectral sensitivity, fowl,

and possibly ducks and turkeys, will perceive the different light sources to be of differing brightness. Prescott and Wathes (1999a) have calculated that fowl would perceive an incandescent bulb as ~20% brighter than a fluorescent tube when illuminated to the same lux level (and therefore iso-luminant for humans). This also has implications for experiments that compare the effects of different light colours, or sources, on the performance, physiology, behaviour and preferences of poultry species, since illuminance levels cannot be matched between treatments without knowing the animals' spectral sensitivity. Studies will therefore confound illuminance with colour if they use different light source or wavelength treatments that are equated for illuminance using the lux unit; as recognised by some authors in their studies (Wathes et al, 1982; Widowski et al, 1992).

The spectral sensitivity of different species may also play an important role in the visual ecology of domestic birds reared under artificial lighting. To a human observer light emitted from the conventional fluorescent and incandescent lights used in poultry housing approximates white light, despite having spectral power distributions very different to that of daylight, which is also described as white (Prescott and Wathes, 1999b). However, to the fowl, light from these sources may be perceived as coloured (Nuboer, 1993; Prescott and Wathes, 1999a). This may affect the successful transmission of any social or other information mediated by colour. For example, if a cue is mediated through red wavelengths it will be transmitted with more success under a light source that produces an abundance of those wavelengths, such as incandescent lighting, whilst its transmission may be hindered or lost under fluorescent lighting which has a spectral output that emits a smaller amount of red wavelengths.

Rearing poultry under artificial lighting that contains little or none of a particular range of wavelengths may deny birds the use of visual cues and capabilities that may be of importance. This may particularly apply to UV_A radiation, which is virtually absent from the spectral output of conventional artificial lighting (Prescott and Wathes, 1999b). Recent work has shown that the feathers of domestic fowl strongly reflect UV_A (Prescott and Wathes, 1999b) and markings in the plumage of turkeys (Sherwin and Devereux, 1999) have been found to be visible under UV_A light. It is suggested that these cues may play a role in social recognition and sexual selection in birds. Other studies indicate that supplementary UV_A lighting may be beneficial for some poultry. Broiler hens prefer to view cockerels that are visible under natural levels of UV_A (Jones

et al, 1999; 2001). It is also preferred by turkeys (Moinard and Sherwin, 1999) and there is some evidence that it may minimise the incidence of injurious pecking amongst these birds (Lewis et al, 2000; Moinard et al, 2001) (see Chapter 2, section 2.3.4). However, experimental studies have not been conducted to determine whether domestic turkeys can perceive UV_A, whilst a behavioural study in mallard (Parrish et al, 1981) contradicts the UV_A sensitivity predicted for this species using microspectrophotometry methods.

As mentioned above, spectral sensitivity can be inferred from electrophysiological studies or by using microspectrophotometry, which determines the wavelength absorption of the visual pigments, corrected for the filtering effects of the five associated oil droplets and the ocular media (cornea, lens and humours). For inferred methods of describing spectral sensitivity see Bowmaker and Knowles, 1977; Jane, 1986; Wortel et al, 1987; Jane and Bowmaker, 1988; Maier and Bowmaker, 1993; Hart et al, 1998; 1999; Hart, 2002. Whilst these methods produce data showing the peak sensitivity of each type of single cone found to be present in the retina, they are only able to show that a bird has the potential for visualising those wavelengths, but do not demonstrate that this information is processed in the brain, nor how strongly the colours are perceived (Neitz and Jacobs, 1989).

Alternatively, psychophysical, or behavioural tests, can determine spectral sensitivity directly. At present, these methods offer the only unequivocal method of determining colour perception, because the animal has to make a learned response based upon what it can see. Behavioural testing can show how sensitive an animal is to a range of wavelengths by the determination of an animal's absolute and relative threshold sensitivity for the wavelengths tested. Data obtained with this method have enabled researchers to derive an alternative unit for measuring fowl-perceived illuminance, the *c*lux (Prescott and Wathes 1999a), which uses the spectral sensitivity of the birds in its calculation rather than that of humans. Using the *c*lux unit to equate different light sources and wavelength treatments for illuminance, as perceived by fowl, has allowed recent research to assess the effects of wavelength and illuminance on these birds independently of each other (Perkins, 2001; Kristensen et al, 2003). At present no such alternative units exist for the duck or turkey. Thus, there are major benefits for using behavioural methods over predicted spectral sensitivity data obtained from other methods. Knowledge of this information for other poultry species like ducks and

turkeys could be of similar benefit for research into the production, behaviour and welfare of these species.

3.2 Aims and objectives

Previous studies have inferred that ducks and turkeys will have similar spectral sensitivities to each other and to domestic fowl, with regard to the majority of their predicted visual spectral range. However, as discussed above (section 3.1) there is some contradiction in the literature as to the sensitivity of ducks to UV_A light (Parrish et al, 1981; Jane and Bowmaker, 1988). Thus, the aim of this investigation was to determine the perceived photopic spectral sensitivity of domestic ducks and turkeys, including the UV_A range, using psychophysical means. In addition, the spectral sensitivity of humans was also assessed to enable a further comparison to be made between ducks, turkeys and humans when they were tested using the same method and illuminance conditions. From this type of data produced it may then be possible to estimate the illuminance perceived by domestic ducks and turkeys for a range of light sources with known spectral power distributions (Chapter 4).

3.3 Materials and methods

3.3.1 Subjects

A total of 25 female turkeys (BUT Big 6, Bernard Matthews Foods Ltd, Norwich, Norfolk, UK) and later 25 female ducks (Cherry Valley Farms Ltd, Market Rasen, Lincolnshire, UK) were reared from one day of age. As there is no precedent to expect the visual systems of male and female birds to differ with regard to colour vision (Hart et al, 1998; 2002), females were chosen (particularly with regard to turkeys) for ease of handling and husbandry. The backs of birds were marked with different coloured symbols, sprayed on with a non-toxic stock marker, to identify individual birds. In total seven birds of each species reached the level of training required to start the experiment (see section 3.3.4 Training), which was started when the turkeys were 119 days (17 weeks) of age and the ducks 133 days (19 weeks). Seven human volunteers, four female and three male, aged between 23 and 30 years old were also tested for comparative reasons. Volunteers had, to the best of their knowledge, normal colour vision without the use of spectacles.

3.3.2 *Housing and husbandry*

During the first 14 days of rearing, birds were housed in a pen with an area of approximately 5 m^2, with wood-shavings litter, a feeder (plastic chick trays, BEC, Stevenage, Hertfordshire, UK) and two drinkers (bucket drinkers, BEC, Stevenage, Hertfordshire, UK). From five days of age, poults were also supplied with three perches (1.8m long x 0.20m high). During rearing the temperature in the pen was reduced from 27 °C after the first 3 days to 16 °C at 14 days and then maintained approximately at this temperature until the end of the experiment. After 14 days of age, birds of both species were given access to a larger pen, measuring approximately 12.8 m^2. For the ducks the original 5 m^2 pen was partially sectioned off and maintained as a "wet area", with access through a wooden barrier via pop holes (0.60 m wide x 1 m high). In this area large automatic drinkers were suspended above metal trays (1 m^2) which were filled with wood-shavings. The design of these drinkers (Jumbo stag drinkers, model WM3E, BEC, Stevenage, Hertfordshire, UK) provided the ducks with a constant water supply to a depth in which they could submerse their bills to beyond the nostril (as recommended by Pingel, 2000). Spilt water from the drinker was caught in the tray and emptied twice daily, to maintain litter quality in the rest of the pen. A larger galvanised metal feeder (Quantag Ltd, Colney Heath, Hertfordshire, UK) was provided for the ducks from 14 days of age. From 14 days of age the turkeys were also provided with a larger galvanised metal feeder and two automatic drinkers (feeder: Quantag Ltd, Colney Heath, Hertfordshire, UK; drinkers: Jumbo stag drinkers, model WM3E, BEC, Stevenage, Hertfordshire, UK).

The birds were fed conventional starter crumbs, starter pellets and rearer rations appropriate to the age of the birds. Ducklings were fed chick starter crumbs (W Jordan & Sons, Biggleswade, UK) for the first 21 days and then waterfowl grower pellets (Allen and Page, Shipdham, UK). The turkey poults were fed turkey starter crumbs for the first 14 days, then turkey starter pellet until 28 days of age, turkey rearer pellets until the birds were 84 days of age (BOCM Pauls Ltd, Ipswich,UK), and finally turkey finisher (Allen and Page, Shipdham, UK) until the end of the experiment. On days that the birds were either trained or tested, food was removed from the pens for 5 hours prior to the start of the training or experimental session, during which birds had the opportunity to work for food rewards. Food was returned to the pen immediately following the end of the session. On all other days food was provided *ad libitum*.

For both species various types of environmental enrichment devices were placed in the pens. These included suspended compact discs, empty feed bags cut into strips and attached to the pen walls, and suspended feed bags with holes cut in them and filled with straw. These were used at various times during rearing with the aim of creating a less barren environment for the birds and to minimising injurious pecking amongst the turkeys. All birds were regularly inspected five times per day throughout the rearing period.

3.3.3 The light environment in the home pens

The lighting system during rearing was provided by six fluorescent 18W tubes (Osram, Biolux, tropical daylight) on timer switches. These lamps approximated daylight in their spectral power distribution, thus giving birds experience of the spectrum of wavelengths that were to be tested in the experiment, including UV_A. The relative percentage spectral power distribution for this light source is shown in Figure 3.1; measured using a spectroradiometer (Model ST2000, Ocean Optics Inc., Dunedin, Florida, USA). The photoperiod schedule for the birds was started at 23L:1D. The dark period was increased by 1 h each day until a photoperiod of 12L:12D was obtained, and this regime was continued until the end of the experiment. A 15 min period of dimmer illuminance was provided before the full daytime lights were switched on and after they were switched off to give the birds "dawn and dusk" periods. The illuminance in the pens was measured at the eye height of the birds by angling the sensor of a calibrated light meter (Model 545, Testo Ltd., Alton, UK) in the direction of maximum radiance, as described by Lewis et al (1999) and Prescott and Wathes (1999b). When the birds were one day old illuminance was measured at 18 points approximately 0.5 m apart within the 5 m^2 pen. At 14 days of age birds were given a larger pen of 12.8 m^2 and the illuminance was re-set to a similar level as before for the new sized pen, taking measurements at 43 points approximately 0.5 m apart within the pen. The illuminance measurements taken on these occasions for the dawn/dusk, full light and dark periods are displayed in Table 3.1. Every week thereafter, the illuminance was measured in the pen/room and adjusted when necessary to maintain the illuminance at bird eye height at the levels stated in Table 3.1 for birds at 14 days of age. Adjustments were achieved by placing or removing black tape from around the fluorescent tubes.

Figure 3.1 The relative percentage spectral power distribution for an 18W fluorescent Biolux tube (Osram, Tropical Daylight; CCT: 6500K), and daylight for comparison.

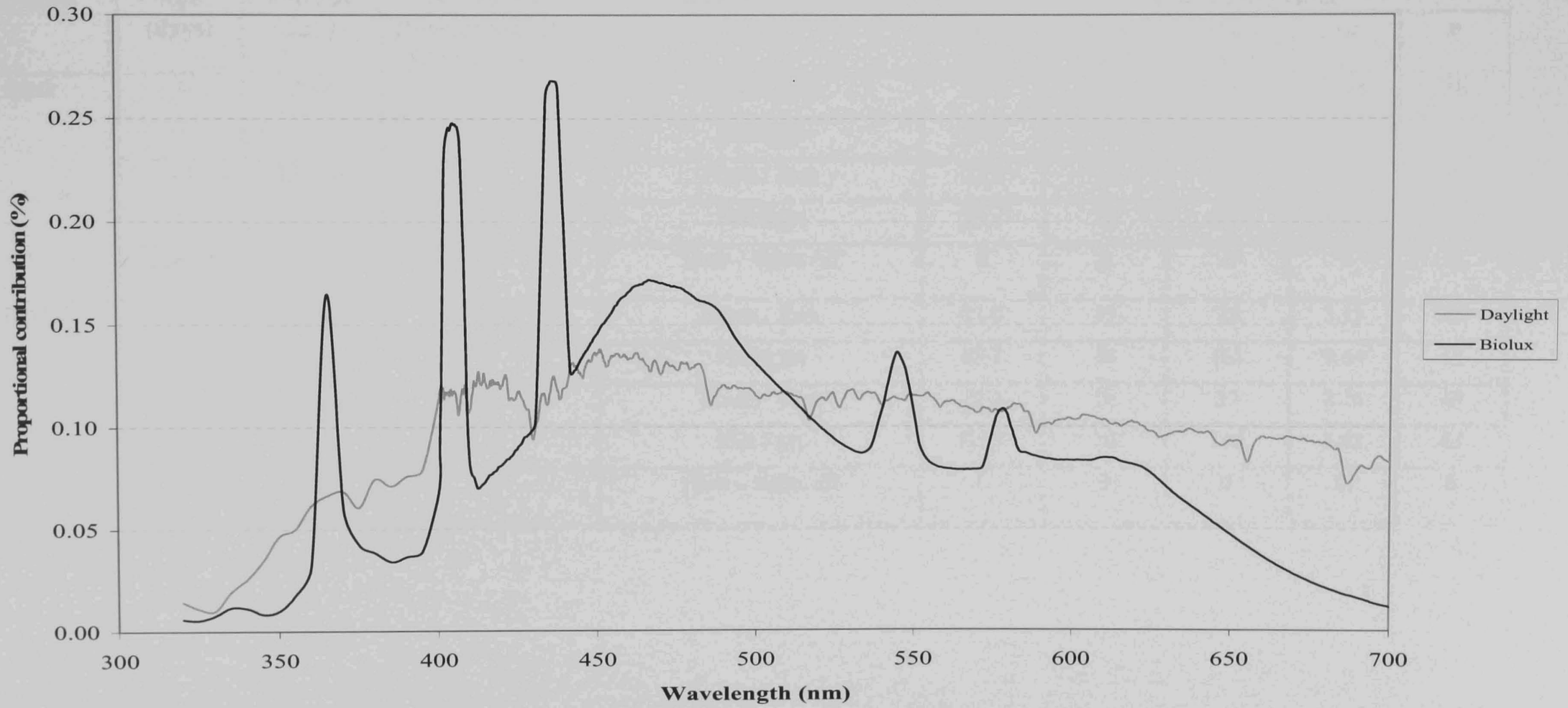


Table 3.1 The illuminance measurements recorded and maintained for the dawn/dusk, full light and dark periods during the duck and turkey rearing for the spectral sensitivity experiment.

Species	Age (days)	Pen size (m^2)	No. of 18W fluorescent tubes (Osram, Biolux)	Lighting Period	Measured Illuminance				
					Mean. (lux)	Min. (lux)	Max. (lux)	sd	n
Duck	1	5 m^2	2	Dawn / dusk	22.2	15	28	3.54	18
			6	Full light	85.9	70	104	9.91	18
	14	12.8 m^2	2	Dawn / dusk	22.3	15	29	3.19	43
			6	Full light	85.7	72	103	8.02	43
	1 & 14	5 m^2 &12.8m^2	0	Dark – lights off	0	0	0	0	0
Turkey	1	12.8m^2	2	Dawn / dusk	21.6	15	27	3.13	18
			6	Full light	85.8	68	101	9.64	18
	14	12.8m^2	2	Dawn / dusk	22.4	16	27	2.76	43
			6	Full light	85.5	70	104	8.42	43
	1 & 14	5 m^2 &12.8m^2	0	Dark – lights off	0	0	0	0	0

3.3.4 Apparatus

The apparatus used in this study and its control system was built at Silsoe Research Institute (Bedfordshire, UK), and were previously used for a similar experiment to determine the spectral sensitivity of domestic fowl (Prescott and Wathes, 1999a). Some modifications were made to adapt the equipment for the different species tested.

3.3.4.1 The operant cage

Birds were placed in a wooden test cage measuring 650 mm x 550 mm, with sides 550 mm high. Three sides of the box were plain wood, and the fourth side incorporated two Perspex panels, through which birds viewed the light stimulus presented, and a metal feeder (Figure 3.2). For the turkeys just one operant cage was used, but for ducks an additional cage of the same dimensions was attached to one side, as the ducklings became easily distressed if isolated. Ducklings were able to maintain social contact with each other through a mesh panel separating the two cages, as shown in Figure 3.3. This additional "buddy" cage did not house any stimulus panels (see section 3.3.5 Training). The cage side that housed the stimulus panels and feeder could be adjusted so that the panels were at eye height for the birds throughout training and the experiment. Attached to the other side of this, outside of the operant cage, was the equipment that provided the food rewards, and the light stimulus (Figure 3.4).

Each of the stimulus panels could be pressed, which automatically delivered a small food reward in the feeder. This was automated by a computer responding to an electronic signal from a micro-switch, which was activated by the panel being pressed. The computer software programme was written at Silsoe Research Institute, and recorded the number of presses made to each panel and could be set to respond with a food delivery if a programmed criterion was met. The floor of the feeder was hinged, so that after a predetermined time following a food delivery, the floor flipped down, dropping any remaining food into a tray outside the cage. This approach was adopted because of the difficulty of providing a measured quantity of food accurately. A camera was positioned at the back of the cage to allow remote viewing of the test bird, the stimulus panels and feeder. Figure 3.5 shows an overview of all the apparatus used for this experiment.

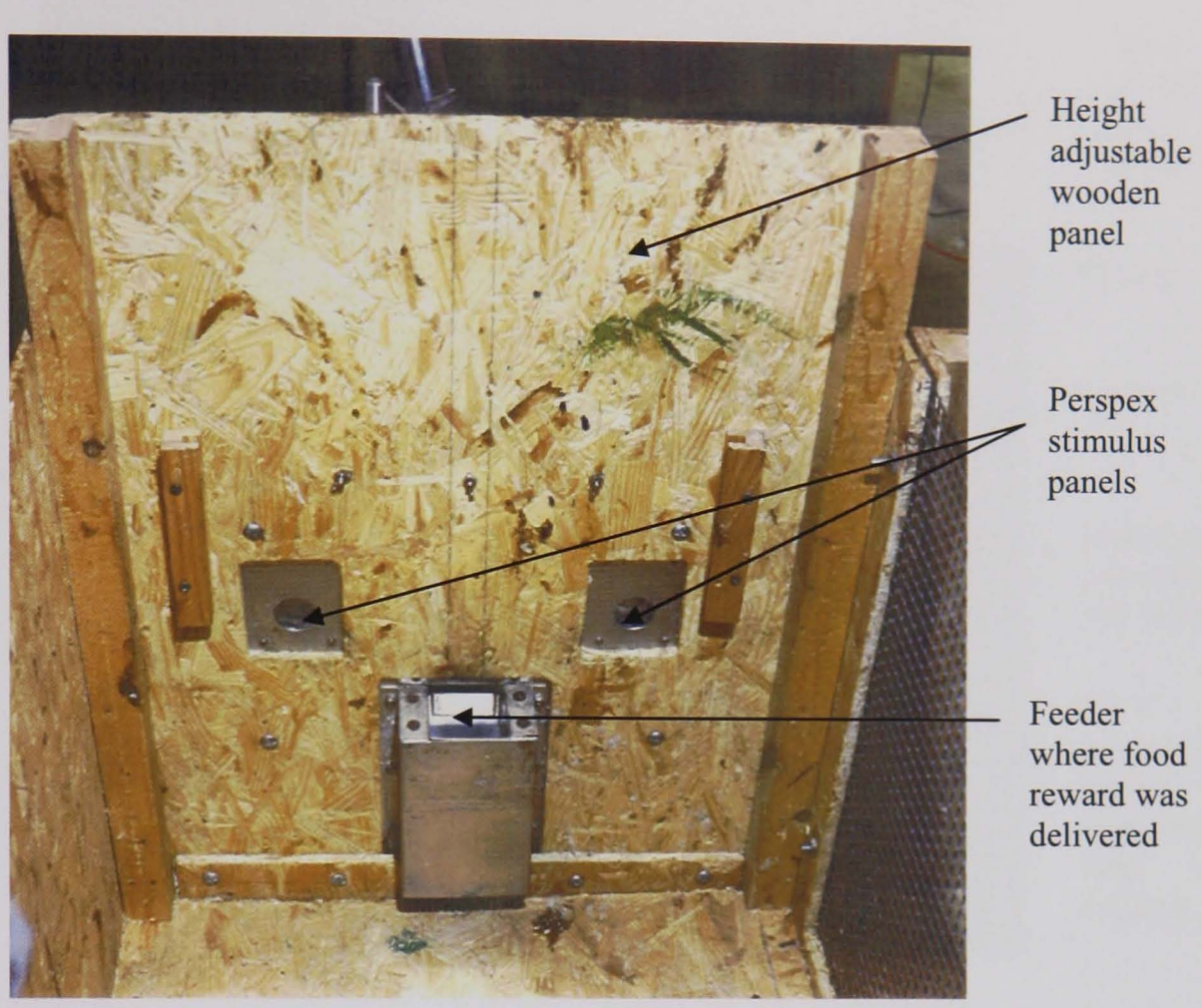


Figure 3.2 Operant test cage showing the two Perspex stimulus panels and feeder

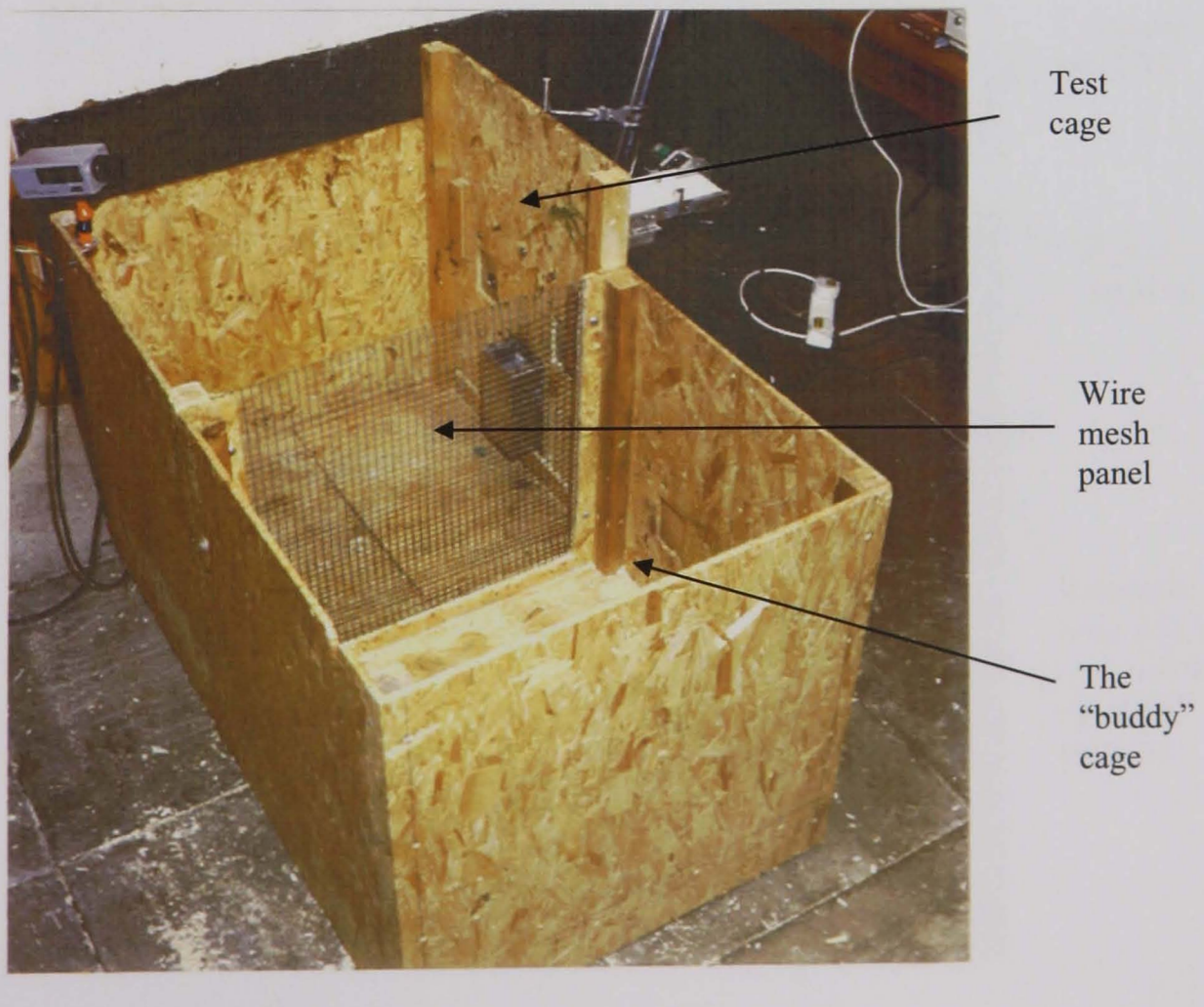


Figure 3.3 The additional "buddy" cage used for the ducks.

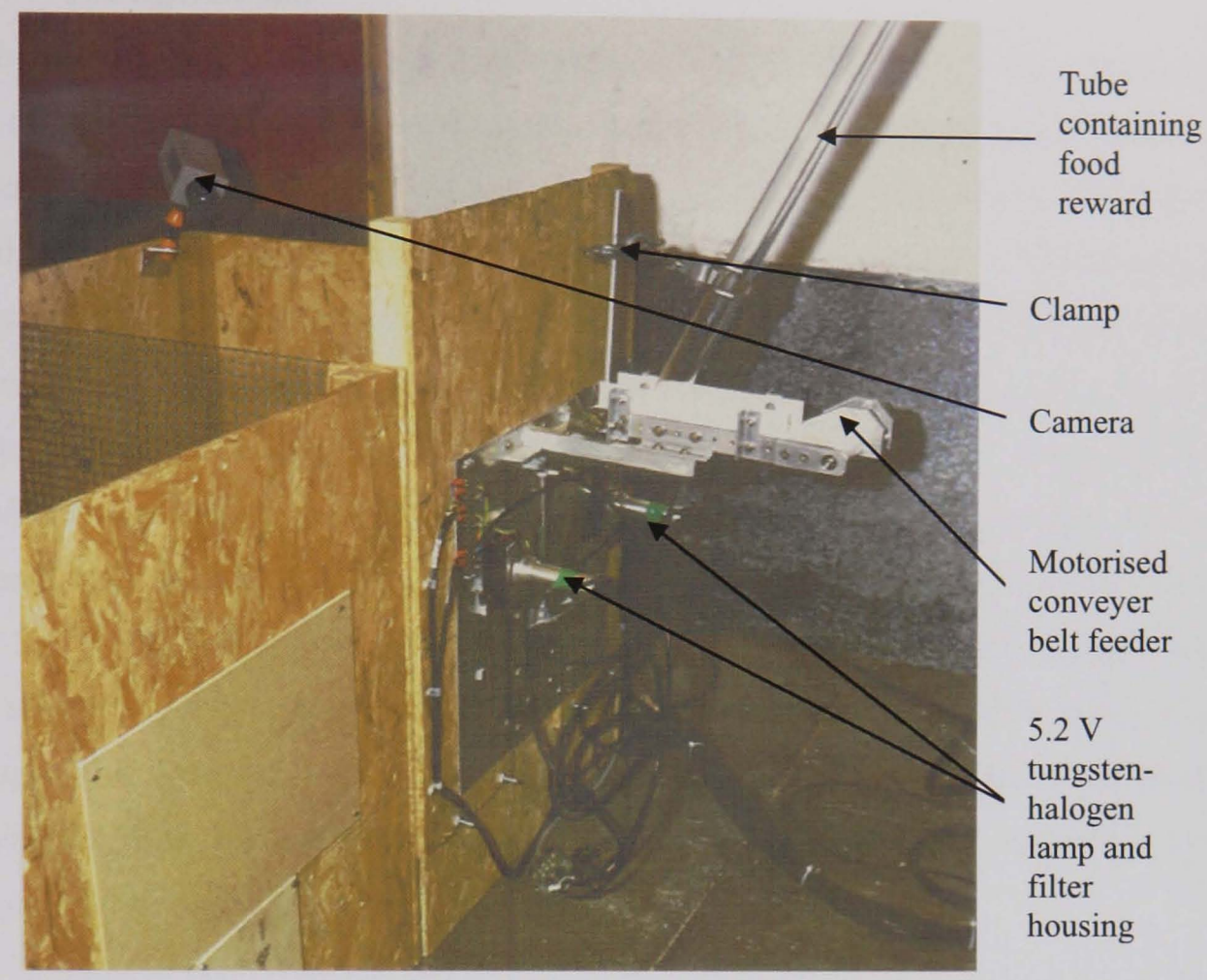


Figure 3.4 The automated feeder and housing for the light stimuli.

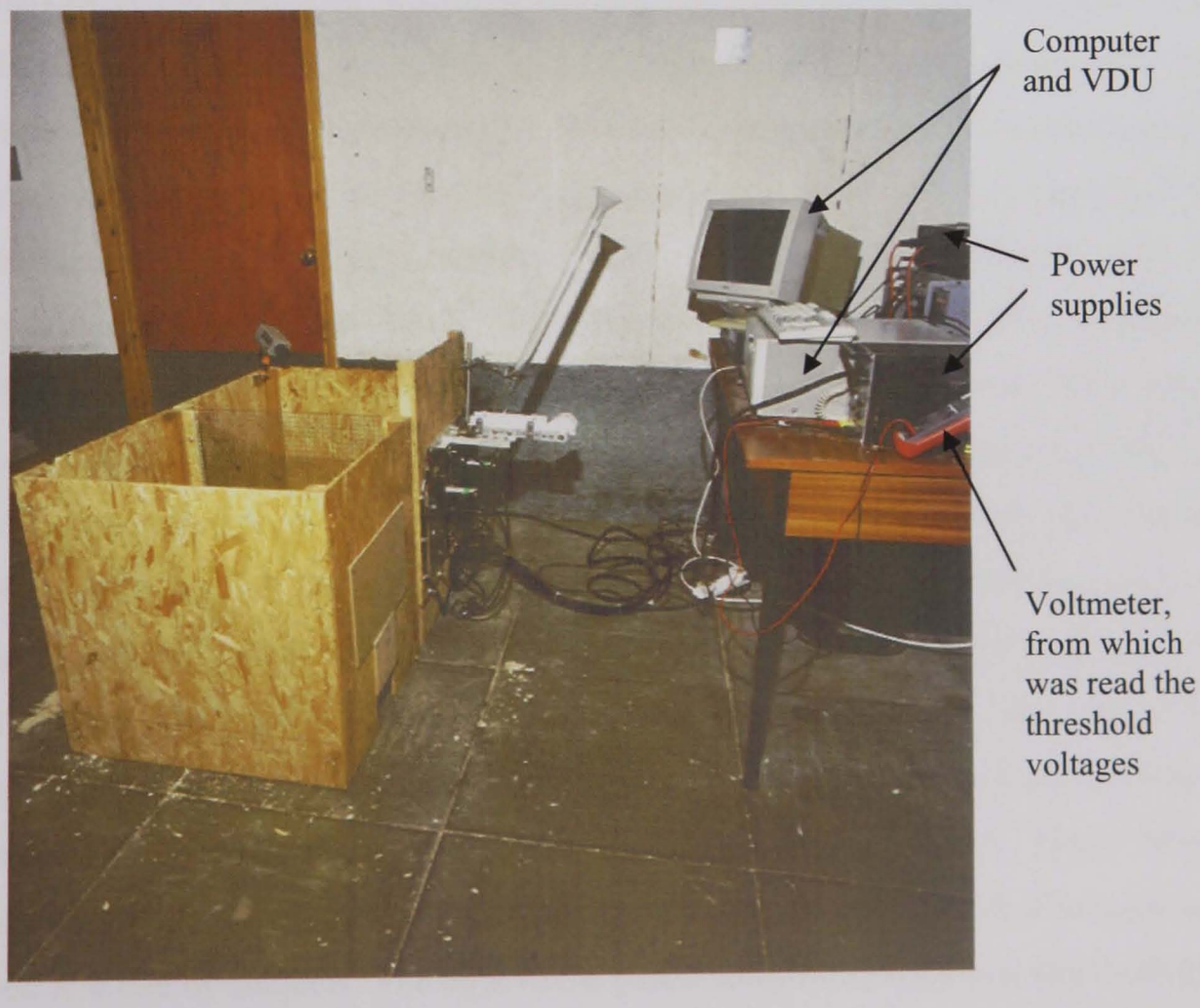


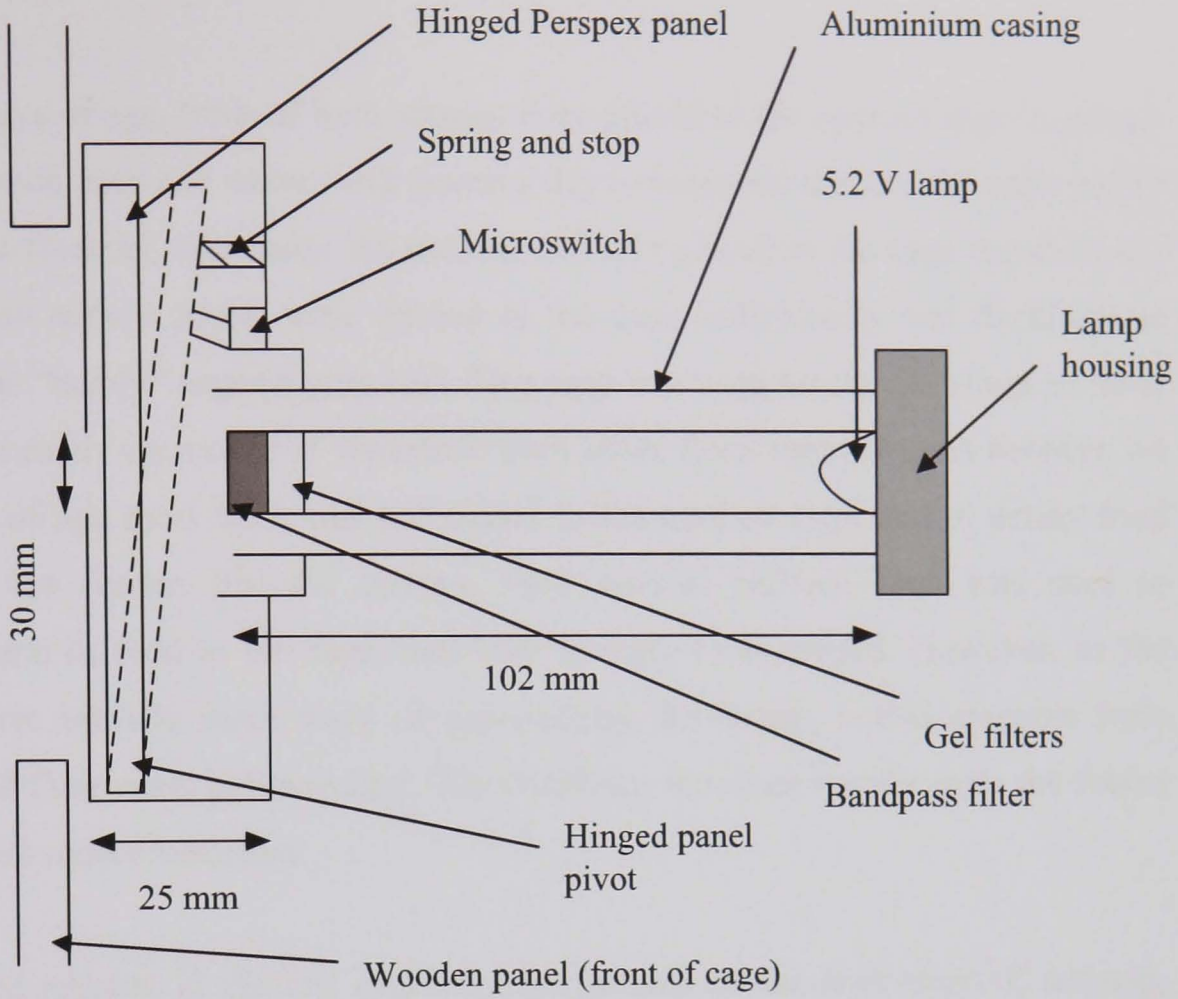
Figure 3.5 An overview of the apparatus with the "buddy" cage.

3.3.4.2 The light stimuli

The light stimuli were contained in metal tubes located behind each Perspex panel. At the end of these tubes nearest the panel, a 12.5mm narrow band-pass filter and layers of diffusion, gel filter (numbers 220 and 416; Lee Filters, Andover, Hampshire, UK) could be fitted. A putty seal was placed around the bandpass filter to ensure no light leakage from around the edge. The other end of the tubes held a 5.2V tungsten-halogen lamp (RS Components Ltd, Corby, Northamptonshire, UK). A cross section through the panel and metal tube is shown in Figure 3.6a. Alternatively, these lamps and housing could be removed and the metal tubes replaced with shorter ones which fitted to wooden boxes, each containing three UV_A fluorescent tubes (Blacklite, F8W/BL350, Sylvania Ltd) (Figure 3.6b). The light sources illuminating each panel were matched for illuminance using a spectroradiometer, and then sealed within the metal tubes or wooden boxes with black tape. This set-up ensured that the only light to reach the panels was from these lamps via the filters. During training and in the experiment only one of the panels was illuminated at a time, the other was unlit.

Identical pairs of narrow band-pass filters (L.O.T. Oriel Ltd) were used to obtain the 13 chosen wavelengths tested in this experiment. These pairs of filters had peak transmittances at the following wavelengths 326, 360, 380, 415, 450, 486, 508, 544, 577, 600, 633, 656 and 694 nm. Little light of other wavelengths was transmitted by these filters; transmittance was reduced by 50% at 10 nm either side of the maximally transmitted wavelength stated above. The light transmission of these filters was stated in the manufacturer's calibration certificates and this was later checked with a spectroradiometer (see section 3.3.7). To transmit light through the UV_A bandpass filters (326, 360 and 380nm), the boxes containing the three UV fluorescent tubes were used. For all other filters the 5.2 V lamps were used. The illuminance of panels could be altered by a combination of reducing the voltage of the 5.2 V lamps and the use of layers of the diffusion, gel filters. The smallest change in voltage that could be achieved with a set number of gel filters was 0.05 V. However, for the UV_A wavelengths (326, 360 and 380nm) illuminated by the UV fluorescent tubes, illuminance was altered by increasing and decreasing the number of diffusion, gel filters, as the voltage for these lamps could not be reduced as for the 5.2 V tungsten-halogen lamps. These tubes remained on throughout testing to prevent the flicker from the light source as it came on being used as a cue by subjects. The light to the panel assigned as dark was shut off by a wooden shutter, manually operated by the experimenter (not shown in Figure 3.6b).

a)



b)

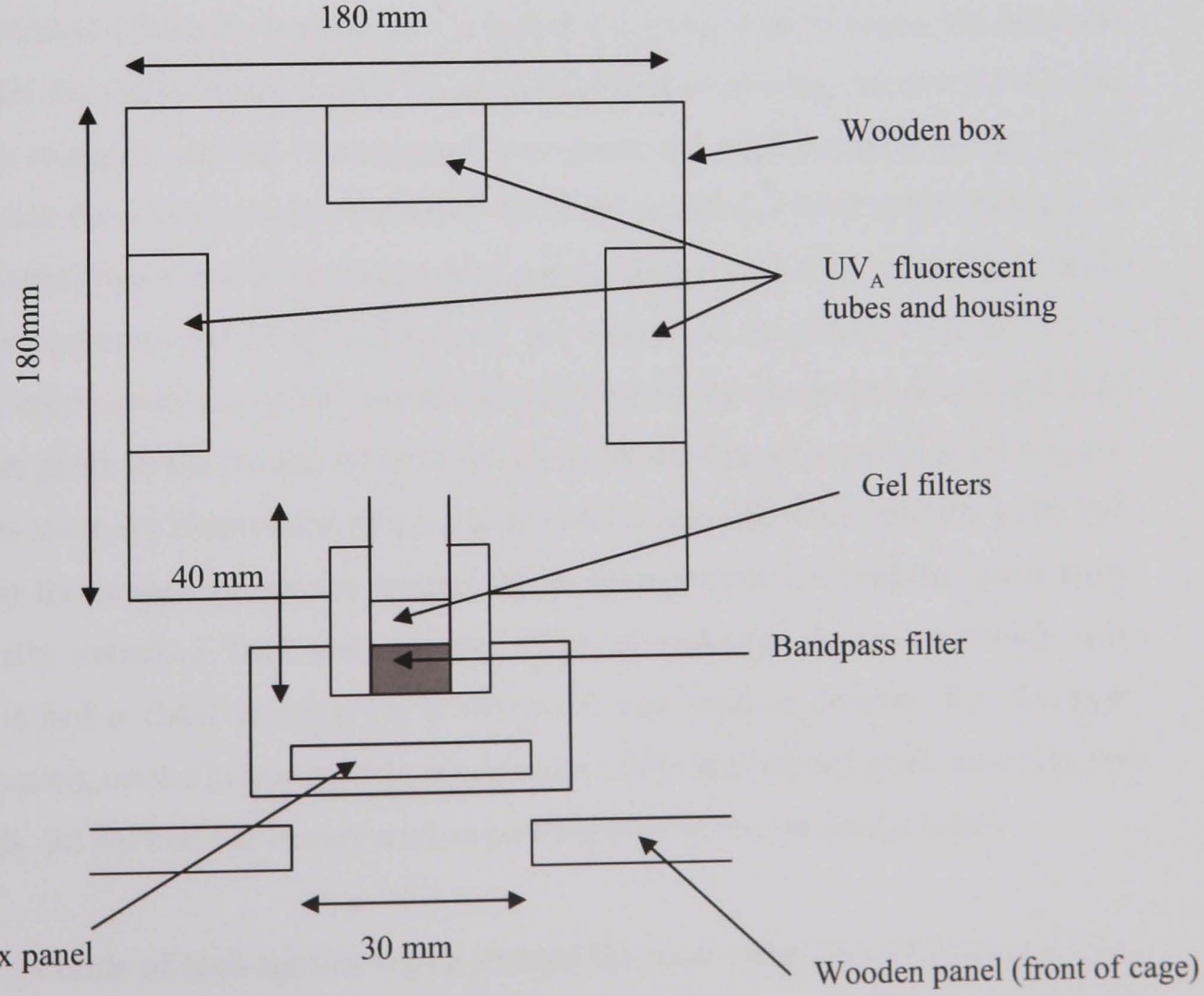


Figure 3.6 Light stimulus and operant apparatus a) cross section of the panel and 5.2 V lamp; b) an overhead view of the UV$_A$ light box and panel (not drawn to scale).

3.3.5 Training

From three days of age, birds of both species were placed in the operant cage in groups of five birds with food and water, each training day to habituate them to the cage and its sounds whilst working. Gradually the number of birds placed in the cage together was decreased until turkey poults were trained in the cage individually and ducklings in pairs using the "buddy" cage (Figure 3.3). This cage was used for the ducklings as these birds became easily distressed if separated from other flock members. At between 14 and 21 days of age most birds had habituated to the operant cage and to eating food provided in the feeder. For the turkeys, their normal pelleted food was used to encourage them to feed in the cage, and later as their food reward. However, as the ducklings were initially more wary of approaching the feeder, boiled maggots were mixed in with their usual pelleted feed. The ducklings fed more readily from the feeder when this food source was used.

Birds that fed reliably in the test cage then progressed on the next stage of training, which was to receive a food reward by pressing once at a panel lit by a bright, white light stimulus. To provide a sufficient level of hunger to ensure motivation to work, food was removed from the home pens 5 h before a training session began. No food was provided for the ducks in the "buddy" cage at this point of training, as after 10 min the birds were swapped and the "companion" was given the opportunity to be the "test" bird and work for a food reward. To attract the birds' attention a food pellet (turkeys) or maggot (ducks) was taped to the illuminated panel, encouraging them to peck or dabble at it. If the pressure used to try and remove the food from the panel was sufficient to trigger the micro-switch, a "peck" would be registered by the computer and a small food reward was given in the feeder, whereas pressing the unlit panel resulted in no reward. The panels were not illuminated when a food reward was delivered, and the birds had 20 s to eat the reward before the hinged feeder floor removed it and the panel lamp automatically switched back on. At this stage of training, the panel which was illuminated had a fixed position for a whole 10 min training session. For the next training session, on the following day, the position of the illuminated panel was changed so the birds did not become accustomed to pecking only at one particular panel.

Later, the 14 birds of each species which showed the most competence (making at least 80% of all pecks made to the correct panel in a trial of 50 presentations of the light

stimulus) were selected for further training. The other birds were removed from the flocks and re-homed. The ducks at this stage were routinely trained in fixed pairs, with the same birds being trained together in all sessions. The remaining experimental birds progressed to being trained to choose between the two panels, only one of which was lit. The illuminated and dark panels were randomly changed after delivery of a food reward. Once the birds had reliably mastered this task, the number of pecks needed to obtain a food reward was gradually increased from one to four, and the time available for the birds to eat it reduced from 20 s to 4 s. The length of the training sessions was also increased to 20 min to enable the birds to complete the approximately 100 trials, necessary for obtaining thresholds in the experiment.

Subsequently, the narrow band-pass filters were used to light the panels at determined wavelengths instead of the bright white light stimulus (provided by the unfiltered 5.2 V tungsten-halogen lamps). Further training to accustom the turkeys to the change from white to coloured light was required, as the birds did not generalise to coloured light as well as was initially expected. Training for the turkeys was modified to encourage the birds to peck the lit panel in a fixed position once for a 20 s reward, but using the coloured stimulus panel instead of white light. The turkeys then repeated the other stages of training given above until birds were achieving 80% correct discriminations of any given coloured stimulus in a training session. Unfortunately, some turkeys failed to generalise to the coloured light and were therefore excluded from further training. To avoid this problem with the ducks, the different coloured light stimuli were introduced earlier in training, as soon as birds had made the association between pressing the lit panel and receiving a food reward.

Finally, when the birds were reliably selecting the panel lit with one of the range of coloured filters, the illuminance of the lit panel was reduced gradually during training sessions by introducing layers of diffusion, gel filter (numbers 220 and 416; Lee Filters, Andover, Hampshire, UK) and reducing the voltage across the lamps. At this stage of training the seven pairs of ducks were assessed to determine the member of the pair which was most consistent during training. This bird was then trained, whilst the other became the companion bird for all further training sessions and the experiment. As the companion ducks were not given the opportunity to work for food, a small amount was provided in the "buddy" cage. When birds reliably selected the correct/lit panel at high illuminances (80% of pecks) and less reliably (less than 80% of pecks) when

illuminance was low, the experiment was started. At this point all birds were routinely working for at least 100 rewards in a training session. In total, seven birds of each species reached the level of training required to take part in the experiment, which was started when the turkeys were 119 days (17 weeks) of age and the ducks 133 days (19 weeks).

3.3.6 Experimental protocol

3.3.5.1 Ducks and turkeys

In each trial a bird was placed in the experimental cage and presented with one dark panel and the other lit by one of the 13 wavelengths, 326, 360, 380, 415, 450, 486, 508, 544, 577, 600, 633, 656 or 694 nm. The order in which the birds and wavelengths were tested was randomised, with all birds being tested on one wavelength over a number of days before another was presented. Which panel was lit and which was dark was also assigned by a random, computer-generated pattern. The bird had to peck at the correct, or lit, panel four times before getting a reward that was available for 4 s. During the reward the panels were not lit. For each wavelength, the starting illuminance was high and this was reduced in steps, with the use of diffusion, gel filters, and/or by reducing the voltage across the lamp, until the birds failed to reach a predetermined criteria. The criteria for the birds making a correct discrimination were that they a) pecked the correct/ lit panel four times with no more than two pecks to the incorrect/ dark panel; b) pecked at this level of accuracy until the lit panel had changed position between the panels five successive times; and c) in the entire sequence of five successive panel changes, a total of no more than four pecks to the incorrect/ dark panel were made (two pecks to the incorrect/dark panel being allowed on two occasions for a sequence). By increasing and decreasing the illuminance of the panel in this region, the minimum level necessary for accurate discrimination could be determined.

The lowest illuminance discernible was defined as the threshold of the bird's sensitivity for that wavelength. For an illuminance to be considered the threshold, it had to be correctly discriminated by the bird three times according to the criteria given above. The illuminance was then reset to an easier discrimination, e.g. the panel was made brighter, and the bird was required to make a further two successful discriminations for rewards. If a bird failed to respond to this easy discrimination, the threshold value it had just completed was discounted. This was conducted to ensure that the reason the bird made

incorrect choices at lower illuminances was due to it being unable to discriminate between the panels rather than because it was no longer motivated to complete the task. Pro-longed disinterest in the panels (longer than 5 minutes) resulted in the bird being removed from the cage, and data from that trial being discounted.

3.3.5.2 Humans

For the seven human volunteers tested, the side of the experimental cage with the panels was removed from the box and fixed vertically to a table-top. Volunteers sat on an adjustable chair so their eyes were level with the panels while seated upright with their eyes approximately no further than 300mm from the panels.

As for the birds tested, the order in which wavelengths were presented was randomised. Each volunteer completed the testing of all wavelengths in one session of 2 h. Which panel was lit and which was dark was also assigned on a random basis. Volunteers were presented with 12 of the previously mentioned 13 wavelengths, ranging from 360 to 694 nm. The wavelength of 326 nm was not tested for humans as there is no precedent to expect humans to be able to see such short wavelengths (Burian and Ziv, 1959; Geeraet and Berry, 1968; Dartnell et al, 1983). Each volunteer was asked to adjust the power supply controls until a setting was found where the colour stimulus was still just visible. This was completed for 10 of the wavelengths tested (415 to 694 nm). The illumination of the 360 and 380nm wavelengths by the UV fluorescent tubes could not be altered in this way. Thus, the illuminance of the panels for these were reduced by the experimenter removing and adding diffusion, gel filter papers behind the panel according to the volunteers' responses. Confirmation of the threshold was achieved by verbal report alone.

3.3.5.3 The light environment in the test room

To ensure that the subjects tested were using photopic rather than scotopic vision, background lighting in the test room was provided by two incandescent lamps (60W, pearl, Osram) positioned overhead. The illuminance in the test room throughout the experiment was maintained at a mean illuminance of ~50 lux (turkeys: mean 50.2 lux, min. 34 lux, max. 68 lux, sd=7.96, n=42; ducks: mean 50.1 lux, min. 37 lux, max. 69 lux, sd=7.59, n=42; humans: mean 49.9 lux, min. 34 lux, max. 67 lux, sd=7.79, n=42). This was measured within the room at the eye height of the birds, or at the eye height of a human volunteer when seated in the chair used during testing. The sensor head of a

calibrated light meter (Model 545, Testo Ltd., Alton, UK) was angled the in the direction of maximum radiance. Shadow in the box resulted in an illuminance of ~9 lux around the feeder and ~25 lux at the panels (not lit). The relative percentage spectral power distribution for this light source is presented in Figure 3.7, measured using a spectroradiometer (Ocean Optics Inc., Dunedin, Florida, USA).

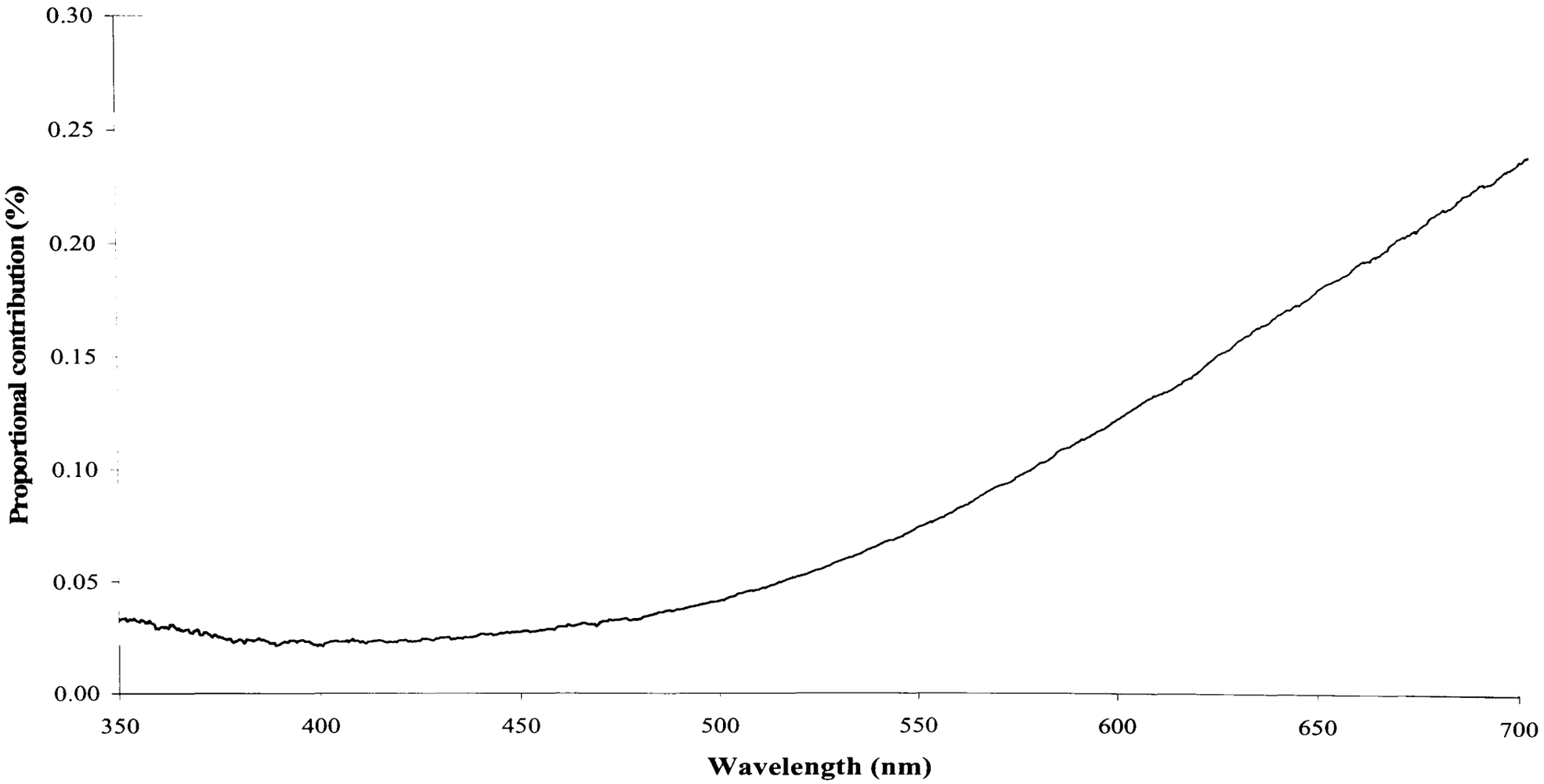
3.3.7 Calibration, data collection and analysis

Prior to the experiment a calibrated spectroradiometer (Ocean Optics Inc., Dunedin, Florida, USA) was used to measure the spectral output and illuminance of the light sources used so pairs of lamps could be matched for use in the experiment. All the narrow bandpass filters to be used were also checked to ensure that the two sets of 13 wavelengths were identical in their transmission of light.

The data collected during the experiment for the wavelengths between 415 to 694 nm were recorded as the lamp voltage (to the nearest 0.05 V) and the number and type of diffusion, gel filters used to reduce the illuminance of the panel to threshold level for each subject. For the UV_A wavelengths (326, 360 and 380 nm) just the number and type of diffusion, gel filters was recorded, as this was the only method used to reduce the illuminance of the lit panel.

The data collected during the experiment were then converted from the lamp voltages and/or the number and type of filter papers used, into units expressing the flux of photons passing through the panel at the threshold levels obtained (photons s^{-1} x 10^{10}). This was done because spectral sensitivity is a function of the flux of photons at a specific wavelength and not the radiant power of the lamps used, and to enable comparisons to be made with other spectral sensitivity curves which are usually expressed in photon flux (Dartnell 1953; Lamb, 1995). The method used to convert the data was similar to that described by Prescott and Wathes (1999a). Each of the threshold values obtained for all subjects at each wavelength were recreated using the exact number of diffusion, gel filter papers and/or voltages used when the threshold was established. The sensor of a calibrated radiometer (Model 1L1400A, International Light Inc., Newbury Port, Massachusetts, USA) was positioned 20mm from the panel and the resulting radiant power was measured in $\mu W\ cm^{-2}$. At this distance the sensors "field-of-view" exceeded the diameter of the light stimulus and it was presumed that the flux

Figure 3.7 The relative percentage spectral power distribution for a 60W incandescent bulb (Osram, pearl) used as background lighting in the test room for training and the experiment.



calculated represented the photons transmitted. For the thresholds obtained for wavelengths between 326 and 380 nm a UV_A sensor was used (SEL038, International Light Inc., Newbury Port, Massachusetts, USA) and for the thresholds at all other wavelengths (415 to 694 nm) a flat rate response sensor was attached to the radiometer (SL021, International Light Inc., Newbury Port, Massachusetts, USA). The radiant power of each threshold ($\mu W\ cm^{-2}$) was then multiplied by the area of the stimulus visible to the subjects (0.64 cm^2) and converted to Watts (W) to give the radiant power of the light stimulus. From this measurement of power, the flux of photons passing through the panel was calculated using the following equation:

$$N = \frac{P\lambda}{hc}$$

Where N = Flux of photons per second, P = Radiant power (W), λ = Wavelength (m), h = Planck's constant ($6.62606876 \times 10^{-34}$ J s), c= Speed of light (2.9979248×10^{8} m s^{-1}).

These converted data were then collated into a Microsoft Excel '97 spreadsheet and the absolute and mean relative spectral sensitivities of the ducks, turkeys and humans were calculated. During the course of the experiment two test birds were removed from the experiment; one turkey was humanely destroyed due to illness and one duck died. The data from these two birds which did not complete the experiment were however, included in the calculations of the respective mean absolute and relative spectral sensitivity curves. Thus the mean absolute spectral sensitivities for some wavelengths were averaged between seven birds and six for others. The other six birds of each species all completed the experiment. For the 326 nm wavelength, only one duck and one turkey were able to discriminate the panels and provide a threshold. These thresholds were excluded from the calculation of the mean absolute and relative sensitivity curves for these species. One human subject (human 6) produced a threshold for the wavelength 380nm, which proved very different to the data for other subjects. This threshold was thus treated as an outlying value and excluded from the calculations of the mean absolute and relative spectral sensitivity curves for humans. The relative mean spectral sensitivity curves were all normalised at 544 nm.

Analyses were carried out using GenStat 5 (Release 4.2, Lawes Agricultural Trust, 1989). To test whether the mean of the absolute and relative spectral sensitivities for

ducks and turkeys was different these data were analysed using a Two-Sample *t*-test for unpaired samples. The degrees of freedom stated are the approximate degrees of freedom calculated in the analyses, which assumed there to be unequal variances between the samples.

3.4 Results

3.4.1 Individual absolute photopic spectral sensitivity

The absolute threshold sensitivities of the individual ducks, turkeys and humans tested are displayed in Figures 3.8, 3.9 and 3.10. The thresholds for duck 5 and turkey 6 are not shown in Figures 3.8 and 3.9 respectively, as only four thresholds for each bird were obtained before their removal from the experiment (due to illness or death) (see section 3.3.7 Calibration, data collection and conversion; for the values of these thresholds see Appendix I, Tables I.1 and I.2). It should be noted that the absolute threshold values given indicate the photon flux (photons s^{-1} x 10^{10}) at the panel and not the incident light on the retina of the subjects.

Figures 3.8, 3.9 and 3.10 show that there was remarkably little variation between the individuals tested for each species. Variation between individuals was greater at the extremes of the spectrum; ultraviolet ($326 < \lambda < 400$ nm) and red ($633 < \lambda < 694$ nm) for ducks and turkeys, and violet ($380 < \lambda < 415$ nm) and red ($633 < \lambda < 694$ nm) for humans. The graphs also generally show subjects to have low sensitivity in these regions of the spectrum, compared to the higher sensitivity and less variation between individuals shown for other wavelengths, particularly between $544 < \lambda < 577$ nm for ducks and turkeys and at $\lambda = 544$ nm for humans. Although there was some variation between individuals, no particular subjects tested were seen to be overall more sensitive than the others of their species. Thus, the results for individuals within species were remarkably similar.

A comparison of the absolute sensitivity thresholds for the ducks and turkeys in Figures 3.8 and 3.9 shows that turkeys are significantly more sensitive than ducks to UV_A wavelengths at λ=360 nm (Two-Sample *t*-test, t=5.21; d.f.=10; P=<0.001) and λ=380 nm (Two-Sample *t*-test, t=4.11; d.f.=6; P=0.007). Ducks only have one area of sensitivity greater than the turkey, and this is at λ=600 nm (orange) (Two-Sample *t*-test,

Figure 3.8 Individual and mean absolute photopic spectral sensitivity of six ducks (thresholds for duck 6 not shown, but included in the mean; duck 3 threshold for λ=326 nm shown, but excluded from the mean for that wavelength as n=1).

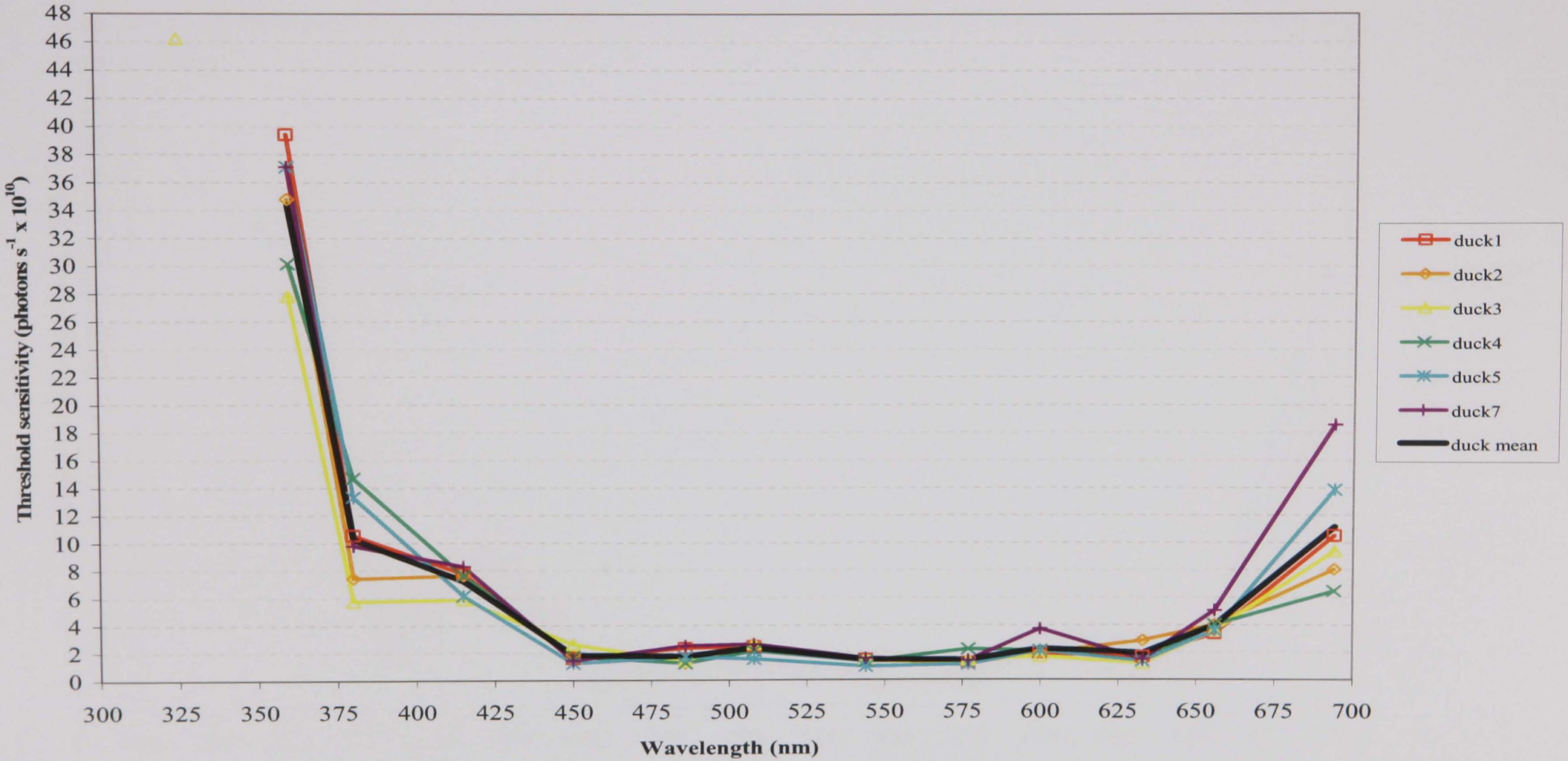


Figure 3.9 Individual and mean absolute photopic spectral sensitivity of six turkeys (thresholds for turkey 5 not shown, but included in the mean; turkey 1 threshold for λ=326 nm shown, but excluded from the mean for that wavelength as n=1).

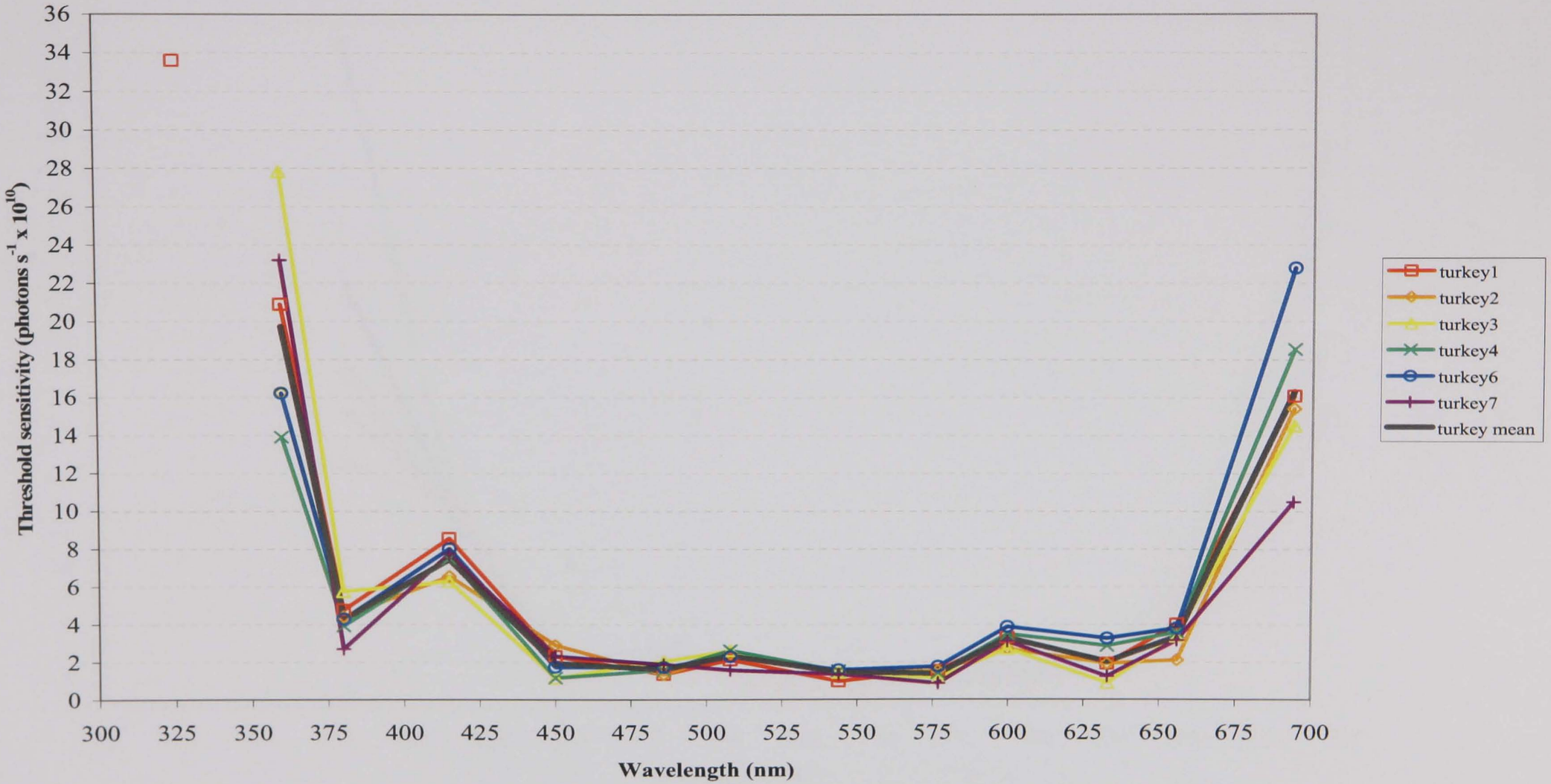
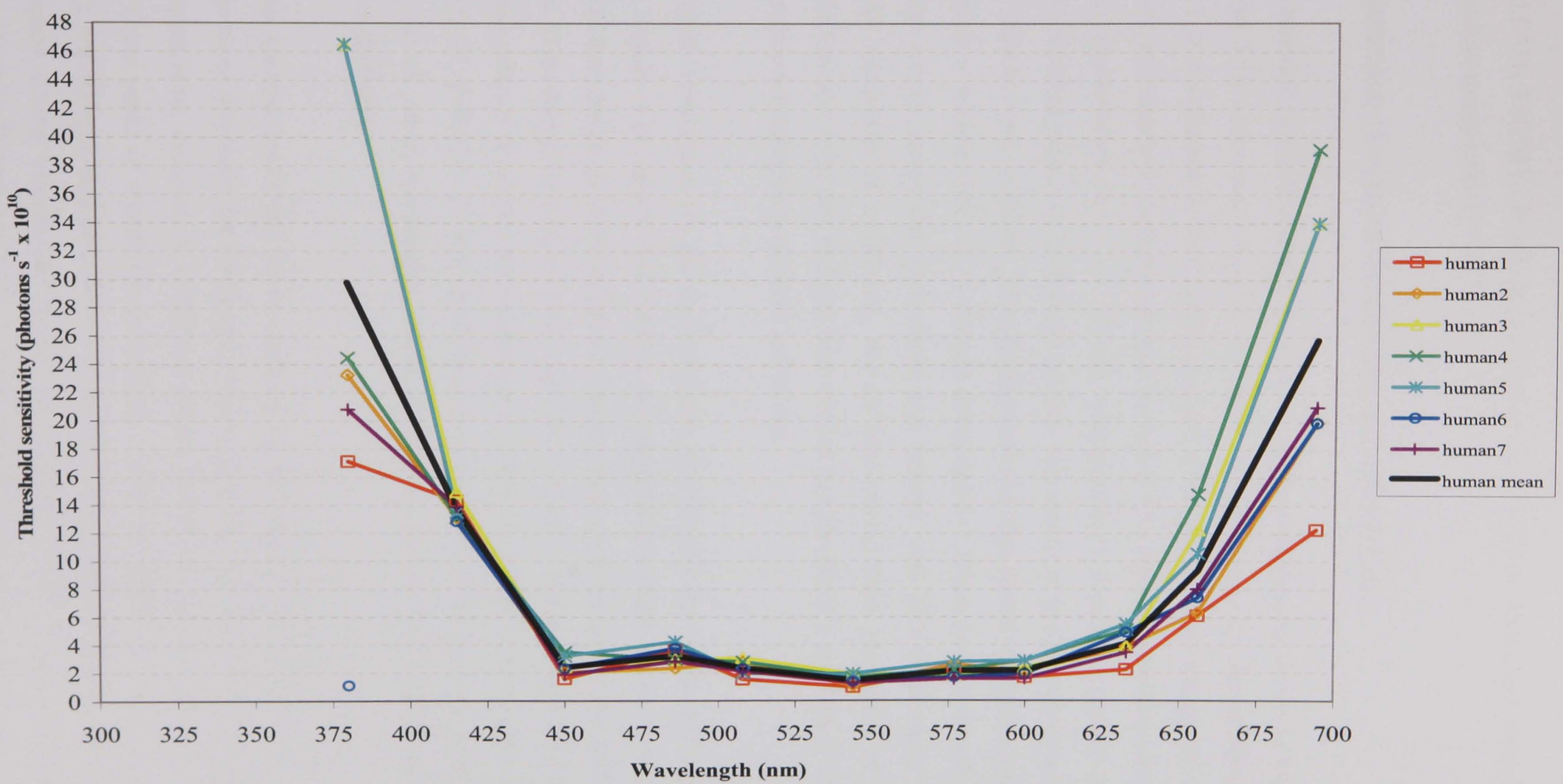


Figure 3.10 Individual and mean absolute photopic spectral sensitivity of seven humans (human 6 threshold for λ=380 nm shown, but excluded from the mean).



t= -3.04; d.f.=11; P=0.011). In all other regions of the spectrum ducks and turkeys had similar absolute sensitivities (P>0.05).

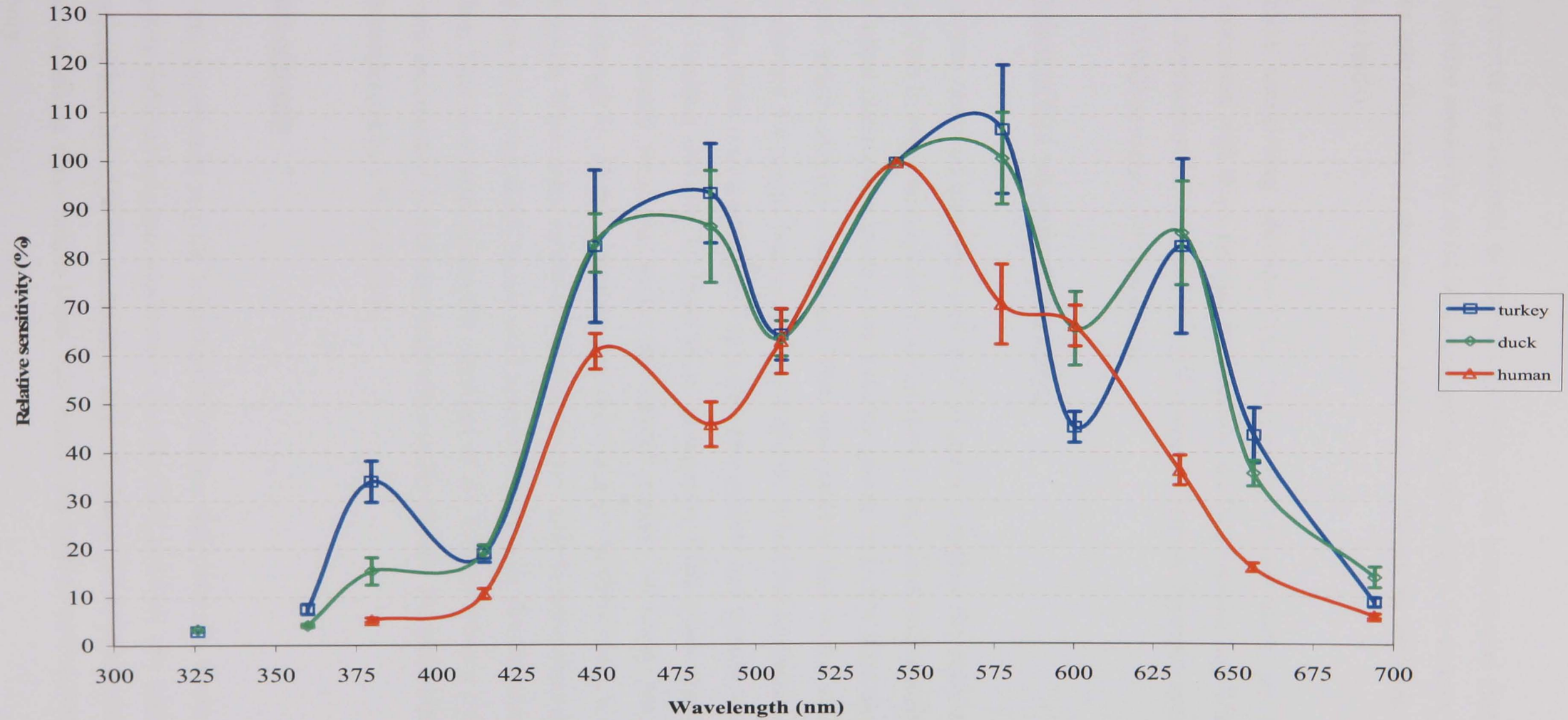
3.4.2 Comparison of mean relative photopic spectral sensitivity

The mean photopic absolute sensitivity of ducks, turkeys and humans shown in Figures 3.8, 3.9 and 3.10 were used to derive the mean relative sensitivity curves shown in Figure 3.11. A comparison of the curves displayed in this graph shows clearly the areas of difference and similarity between the species tested. The highest sensitivity of ducks and turkeys was between $544 < \lambda < 577$ nm, with sensitivity decreasing sharply either side of this maximal peak. For both avian species, this results in two depressions in the curve at λ=508 nm and λ=600 nm. Two further peaks of high sensitivity were observed for these birds at between $450 < \lambda < 486$ nm (blue) and λ=633 nm (red). A fourth peak in the avian curves shows that both ducks and turkeys were able to perceive UV_A wavelengths maximally at λ=380 nm. For all birds tested their perception of UV_A extended as low as λ=360 nm, and one bird of each species (duck 3 and turkey 1) was able to perceive wavelengths as short as λ=326 nm.

The statistical comparison of the mean relative sensitivities for ducks and turkeys shown in Figure 3.11 shows that turkeys are significantly more sensitive to UV_A wavelengths than ducks at λ=360 nm (Two-Sample *t*-test, *t*=-2.99; d.f.=6; P=0.023) and λ=380 nm (Two-Sample *t*-test, *t*=-3.60; d.f.=10; P=0.005). However, ducks show a greater mean relative sensitivity than turkeys at λ=600 nm (orange) (Two-Sample *t*-test, *t*= 2.62; d.f.=11; P=0.024). As with the statistical comparison of the absolute sensitivity thresholds, at all other wavelengths tested, ducks and turkeys had similar absolute sensitivities (P>0.05).

The human spectral sensitivity curve obtained in the present study (Figure 3.11) is different to those displayed for ducks and turkeys. Humans have three rather than four peaks of sensitivity, maximal at λ=450 nm (blue), λ=544 nm (green) and λ=600 nm (orange). These peaks of sensitivity are located at different points in the spectrum to both ducks and turkeys, and also show that humans have lower sensitivity than these birds at nearly all the wavelengths tested. An exception to this is the sensitivity of humans to wavelengths between $577 < \lambda < 633$ nm (yellow to red). In this region of the spectrum humans were more sensitive than turkeys, but less so than ducks. Whilst

Figure 3.11 The mean relative spectral sensitivity (with SE) of ducks, turkeys and humans, normalised to a sensitivity of 100% at 544 nm (relative threshold for human 6 at λ=380 nm excluded; relative thresholds for duck 3 at λ=326 nm and turkey 1 at λ=326 nm shown).



humans could perceive wavelengths as low as λ=380nm in this investigation (but not λ=360nm), the relative sensitivity of the birds was greater, particularly for turkeys, and extended further into this area of the spectrum (down to λ=360 nm for all birds; and λ=326 nm for two birds).

The mean relative sensitivities obtained from data in the present study are later compared and discussed with those derived for domestic fowl by Prescott and Wathes (1999a) using a psychophysical test and the CIE standard human photopic spectral sensitivity curve (1983) in section 3.5 Discussion.

3.4.3 Observations of bird responses during testing

During testing it was observed that most birds took longer to complete the trials when the illuminance of the lit panel was reduced to levels close to their threshold sensitivity. Birds were also often observed to move away from the panels and view them from a variety of angles before making a selection. This was possibly due to the task of discriminating between the panels becoming more difficult. When the illuminance of the panel was high, birds selected the panel to press more quickly and usually viewed the stimulus by standing directly in front of it. Sometimes birds made incorrect discriminations or would press the panels the correct number of times, but not sufficiently hard enough for all to be registered by the computer. In these cases, a food reward was not given. When these incidents occurred several times in succession, some turkeys were observed to peck at the panels indiscriminately and at the feeder, possibly out of frustration. This was most commonly observed in the turkeys when a correct discrimination was unrewarded. In contrast, most of the ducks usually persisted with the task, even if not reinforced by a food reward.

3.4.4 Summary of results

The results of this experiment provide behavioural evidence that domestic ducks and turkeys have subtly different spectral sensitivities to each other and both can perceive UV_A wavelengths as low as λ=360 nm to different degrees. Compared to humans tested under the same conditions these results show that ducks and turkeys have a broader spectral sensitivity.

3.5 Discussion

The overall objective of this experiment was to determine by psychophysical methods the perceived photopic spectral sensitivity of domestic ducks and turkeys. Previous studies have inferred that there may be some difference between the species, particularly with regard to their sensitivity to UV_A wavelengths. The degree to which ducks would be able to perceive wavelengths in this range was also disputed in the literature, with some contradictory findings reported. A further aim was to determine the spectral sensitivity of humans under the same test conditions for comparative purposes.

3.5.1 Comparison of spectral sensitivity curves to previous work

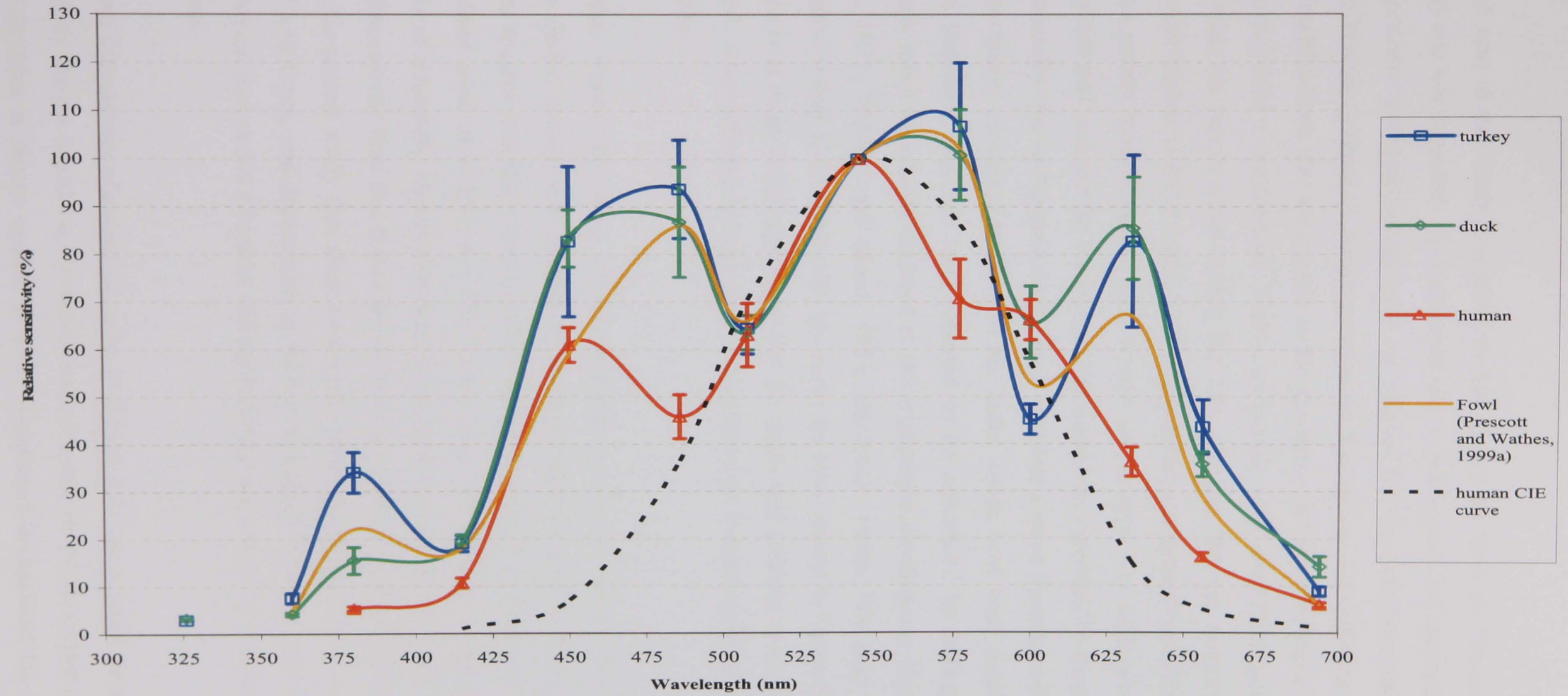
This experiment provides behavioural evidence that domestic ducks and turkeys are able to perceive a broad range of wavelengths, extending from in the UV_A (λ=360 nm) to red (λ=694 nm) ranges of the spectrum. This supports the findings of microspectrophotometry studies in the duck (Jane and Bowmaker, 1988) and the turkey (Hart et al, 1999) which predicted that both these species would have tetrachromatic colour vision encompassing some degree of UV_A sensitivity, conferred by the presence of a violet-sensitive (VS) single cone and its association with a transparent oil droplet. The findings of this experiment are consistent with the prediction of Hart et al (1999) that turkeys will have considerable sensitivity to UV_A wavelengths between $315 < \lambda < 400$ nm. In contrast, Jane and Bowmaker (1988) predicted that ducks would be relatively insensitive to UV_A wavelengths. In some agreement with Jane and Bowmaker (1988) ducks were found in the current investigation to have a reduced sensitivity to UV_A wavelengths compared with the turkeys. However, whilst all ducks were able to perceive UV_A light at λ=360 nm, as predicted by Jane and Bowmaker, the single observation of UV_A perception by duck 3 at λ=326 nm is contrary to this previous study. Their findings showed that the ocular media (cornea, lens and humours) of the duck eye significantly absorbs rather than transmits short wavelengths below λ=400 nm, with 50% transmission occurring at about λ=370 nm and only 1% transmission at about λ=340 nm. In the comparable study of the turkey by Hart et al (1999), the ocular media of the eye were found to transmit UV_A wavelengths down to λ=315 nm, with 50% transmission occurring at λ=358 nm.

Parrish et al (1981) used behavioural data obtained from heart-rate conditioning experiments to determine UV_A perception in the mallard. As in many classical conditioning studies designed to investigate the limits of perception, Parrish et al (1981) used an aversive unconditioned stimulus of a weak electric shock for about 0.5 s immediately following the presentation of a monochromatic light stimulus for 10 s (the conditional stimulus). A conditioned cardiac response was gained for most birds after three trials. During testing, a positive response was scored if the heart rate recorded during the light stimulus presentation was $\leq$ 20 beats/min than the heart rate recorded in the 6 s preceding exposure to the light stimulus. These results indicate a maximal response to UV_A in the $340 < \lambda < 360$ nm range. Such findings do not correspond to the results of the current study which shows ducks to have a maximal sensitivity to UV_A at λ=380 nm, and for sensitivity to be much lower at λ=360 nm. It can only be suggested that the discrepancy between these two psychophysical tests is due to the different methodologies used and/or the different configurations of the light stimulus. Unfortunately, Parrish et al (1981) do not give a full enough description of these to enable a proper comparison.

Figure 3.12 further compares the mean relative sensitivities obtained in the present study with that determined by Prescott and Wathes (1999a) for domestic fowl. The curves for the three species are alike, showing four peaks of sensitivity in similar locations of the spectrum. However, this experiment shows that the magnitude of the sensitivity between the three avian species is slightly different at some wavelengths. Compared to fowl, ducks have an equal or slightly increased sensitivity to all the wavelengths tested apart from those in the UV_A range between $360 < \lambda < 400$ nm. In comparison turkeys show an equal or increased sensitivity at all wavelengths apart from λ=600 nm (orange) where the fowl is slightly more sensitive. However, in most cases the relative spectral sensitivity curve for the domestic fowl (Prescott and Wathes, 1999a) falls within close range of the standard error bars for the duck and turkey data.

The similarity between the spectral sensitivity curves for ducks, turkey and fowl is not surprising. Microspectrophotometry methods have previously shown that the four types of visual pigments in the retina of ducks, turkeys and fowl have almost identical peak absorbencies (see Chapter 2, Table 2.2). The difference in the UV_A perception by the duck compared to that found for turkeys and fowl was predicted by Jane and Bowmaker (1988) (see above). However, the increased sensitivity of turkeys to UV_A wavelengths

Figure 3.12 The mean relative spectral sensitivity (with SE) of ducks, turkeys and humans, normalised to a sensitivity of 100% at 544 nm compared to spectral sensitivity data for the domestic fowl (Prescott and Wathes, 1999a) and the CIE standard human curve (1983).



(360 < λ < 415 nm) in this study compared to that shown for fowl by Prescott and Wathes (1999a) was not expected. As mentioned above (see section 3.4 Materials and methods) the apparatus and methodology used was adapted for this study from that used by Prescott and Wathes (1999a). A possible reason for this unexpected difference may be due to the modifications that were made to the apparatus and test conditions in the current study to that used to test the fowl. Firstly, the present study used UV fluorescent tubes to illuminate the panels when testing the 326, 360 and 380 nm wavelengths, whilst Prescott and Wathes (1999a) used a 12 V tungsten-halogen lamp (Poland Ltd.). It is possible that a greater transmission of light at these wavelengths was achieved using the UV tubes which may account for the higher UV_A sensitivity recorded for the turkey in this study. Secondly, the background illuminance used was a mean illuminance of 50 lux in this experiment, compared to the 100 lux under which fowl were tested. As psychophysical threshold data has been reported to be influenced by background illuminance, with lower thresholds obtained at lower photopic illuminances (Sperling and Harwerth, 1971; Nuboer and Moed, 1983; Bartleson, 1984), this may be a contributing factor. It may also explain why the curve for fowl, shown in Figure 3.12 is very slightly lower at most wavelengths than that for ducks and turkeys, apart from at the points noted. Alternatively, turkeys may simply have an increased sensitivity to UV_A wavelengths.

Figure 3.12 also shows the mean relative spectral sensitivity curves from this experiment for ducks, turkeys and humans to be very different to the CIE standard human photopic spectral sensitivity curve (1983); which is a smooth bell-shaped curve with one maximal peak at λ=550 nm. The results from the present study display additional peaks of sensitivity, clearly showing ducks and turkeys to have a broader and greater spectral sensitivity than that shown for the human by the CIE curve (1983). The human data in the present study also show two additional peaks of sensitivity at about λ=450 nm and λ=600 nm, and depressions in the curve at about λ=486nm and λ=577 nm. This experiment thus shows a broader and generally greater sensitivity than the CIE curve for humans.

These peaks and depressions of sensitivity seen in Figure 3.12 are a noted pattern in spectral sensitivity curves based on threshold measurements in psychophysical tests where the test-stimulus is shown against a white illuminated background (as in the

present study) (Bartleson, 1984; Nuboer, 1986). In contrast, the CIE standard human curve is based on data obtained using flicker photometry research, the results of which do not show this response pattern and are collected under different test conditions (Kaiser, 1984). Similar shaped curves have been observed in humans and other primates, yielding curves with two dips at about λ=480 nm (blue-green) and λ=580 nm (yellow) and three distinct peaks in the blue (λ=445 nm), green (λ=525 nm) and red (λ=615 nm) parts of the spectrum (Sperling and Harwerth, 1971; Nuboer, 1986). The human curve determined in the present study is thus in good agreement with those determined by other studies using similar test conditions and methodologies. The depressions observed in the curves of trichromatic humans and primates tested in this way have been interpreted as reflecting the lateral inhibition of the blue-yellow and red-green colour channel opponent processes. A brief explanation of a human opponent-process model is given in Appendix II. According to this model, the depressions observed in the human sensitivity curve in the present study are the result of inhibition of the signals from the short wavelength-sensitive cones (SWS) by signals from either the medium wavelength-sensitive cones (MWS) or the long wavelength-sensitive cones (LWS) or the two combined (MWS + LWS) through the blue-yellow opponent channel or *vice versa*; and the inhibition of signals from long wavelength-sensitive cones (LWS) cones by signals from the medium wavelength-sensitive cones (MWS) cones or *vice versa* through the red-green channel (Bartleson, 1984; Kaiser, 1984; Nuboer, 1986) (see Appendix II, Figure II.1). Studies in monkeys have shown that this neural processing of colour information begins to take place in the ganglion cell layer and transfers through the fibres of the optic nerve to the *lateral geniculate nuclei*, and then onto the visual cortex (De Valois and De Valois, 1975; cited by Coren et al, 1979). Whether this neural pathway for processing such visual information is the same for birds is unknown.

A study by Osorio et al (1999) has found evidence that a more complex system, based on at least three opponency mechanisms or channels may be employed in domestic chicks. It is suggested that this system of tetrachromacy uses all four types of single cone cells found in the fowl. One channel compares the output signals from the violet and short wavelength-sensitive cones (SV channel), another compares the output signals from the medium and long wavelength-sensitive cones (LM channel) and a third compares the output signals of the short and long and/or medium wavelength-sensitive cones ((L+M)S channel). This study does not exclude a role in colour vision by the double cones, but the authors suggest that these photoreceptors serve luminance-based

tasks instead (Osorio et al, 1999). It is therefore, reasonable to propose that such systems of colour vision and opponent-process mechanisms also function in the duck and turkey, although this remains to be tested experimentally.

This aspect of lateral inhibition may also offer a possible explanation for the difference previously noted in the lower sensitivity of turkeys at λ=600 nm compared to fowl and ducks. Inhibition of signals from the long wavelength-sensitive cones (LWS) by the medium wavelength-sensitive cones (MWS) through the LM (or red-green channel) may be greater in these birds. The reduced width of the "red" peak in turkeys compared to fowl and ducks also implies greater lateral inhibition by this channel.

An observed asymmetry of inhibition in mechanisms of opponent-processing in humans and other primates may also provide an explanation as to why the peaks of sensitivity observed for ducks, turkeys and humans in this experiment do not correspond with the maximum absorbance (λ_{max}) of visual pigments identified by microspectrophotometry methods in these species (see Table 2.2), or the predicted spectral sensitivities estimated from these absorbencies. For humans and other primates, the discrepancy between spectral sensitivity determined using increment threshold psychophysical tests (as used in this experiment) and visual pigment absorption data has been noted (Nuboer, 1986). As the inhibition of LWS cone signals by MWS cone signals is considered to be much stronger than when reversed, the long wavelength peak found in threshold psychophysical studies is often narrower than that predicted by its absorption curve in microspectrophotometry. Its maximum peak is also shifted about 55 nm towards longer wavelengths from λ=558 nm (Dartnell et al, 1983) to about λ=615 nm (Sperling and Harwerth, 1971). The maximum of the short wavelength peak is also shifted to longer wavelengths in these types of studies, due to the strong absorption of short wavelengths by the primate and human lens (Nuboer, 1986). As Osorio et al (1999) have found evidence of opponent-process mechanisms in fowl, it is possible that similar effects as shown for humans could explain the discrepancy between microspectrophotometry data and the results of the current study. It may be that the inhibition of VS cone signals by SWS cones shifts the peak of this cone in psychophysical tests towards shorter wavelengths, as observed in the current study. The transmission of UV_A light by the ocular media of the turkey and fowl eye, and limited amount transmitted in the duck eye may mean that the shift of the short wavelength peak in avian species to longer wavelengths does not occur. However, this has not yet been shown experimentally.

3.5.2 Benefits and limitations of method

Whilst it would have been preferable to have tested as large a sample size of ducks, turkeys and human subjects as possible, the numbers used for this study were limited by the time available to train the birds and the availability of the human volunteers. However, the sample size of six ducks, six turkeys and seven humans is comparable to the numbers used in other studies to elucidate the spectral sensitivities of other avian species. In psychophysical studies of the pigeon (Blough, 1957), the Pekin robin (Maier, 1992) and the domestic fowl (Prescott and Wathes, 1999a) sample sizes of three, two and seven respectively were used. Further, a colour discrimination study in turkeys (Smith et al, 1989), using an operant technique had a sample size of one bird.

It is possible that the criteria for selecting the birds for the experiment (see section 3.3.5 Training) may have created a bias towards birds with some better aspect of vision and/or ability to learn in the sample tested. Unfortunately, due to time constraints it was not possible to give the excluded birds the extra training required to enable them to start the experiment. The selection of the human sample was not subject to any requirements other than the availability of volunteers under 30 years of age with, to the best of their knowledge, "normal" colour vision. The age restriction was to avoid adding variability to the results due to the possible effects of age on vision, which was not a factor for the bird data. In humans, there is a decrease in light transmission with age, particularly at the blue end of the spectrum, resulting from a "yellowing" of the lens (Bron et al, 2000).

A benefit of the presentation of the stimuli being mounted on one side of a wooden cage was that the birds were relatively free to move about and choose their position from which to view the panels. Some studies have shown that avian species have specialised regions in the retina utilised for different visual tasks e.g. lateral monocular vision for movement detection and frontal field vision for finer detail (Shizmu and Karten, 1993; cited by Dawkins and Woodington, 1997). Further, electrophysiological studies by Wortel et al (1987) found that different threshold spectral sensitivities could be obtained for the ventral and dorsal areas of the retina in domestic fowl. It is not known if ducks and turkeys have specialised regions of the retina used for different visual tasks, but in the present experiment the freedom of movement in the cage should have ensured that the birds were able to use either lateral or frontal vision to view the panels. This would allow images to be projected onto any part of the birds' retina.

The experimental protocol was designed to enable the birds to answer the question "what is the minimum illuminance at which you can perceive this wavelength?" Thus, a particular set of criteria was required to determine a successful from an unsuccessful discrimination (see section 3.3.6 Experimental protocol). The option of presenting rewards when only the appropriate number of strikes to the illuminated/correct panel and none to the dark/incorrect panel would have had the advantage of making the threshold of discrimination clearer. This approach could not be used due to limitations in the software and the operant equipment. Not all pecks made by birds were of sufficient accuracy or pressure to trigger the micro-switch and be registered by the computer. Sometimes birds would peck the correct panel the required number of times, but at least one would fail to register. If a food reward was not delivered the birds would proceed to peck indiscriminately at the panels and the feeder, possibly out of frustration. An anomaly in the software allowed the birds to continue to do this until the correct panel had been depressed the designated number of times and a food reward was given. To avoid this it would have been helpful if neither panel responded to presses for a period of time after the incorrect panel was chosen. Modifying the design of the panels so that birds pulled a cord or toggle may have been easier for the birds to manipulate. It would also have been a more natural action for the birds to make, particularly for ducks which "dabble" rather than "peck" at objects.

Instead, to overcome these limitations, the criterion for a successful discrimination used allowed the birds to make a certain number of "errors", but was still accurate enough to determine that the birds were not discriminating by chance (see Appendix III for a description of how this was determined). With the criterion set, the birds had to choose the illuminated/correct panel with a minimum of 85.71% of pecks made to the correct panel to achieve a successful discrimination. However, because of the randomisation of the panel presentation and the fact the lit panel was required to change position five times, the percentage of correct pecks required was often greater, usually above 90%, according to the number of panel presentations in the sequence. Additionally, the criterion also proved that birds did not stop working for rewards because they were no longer hungry or motivated to do the task. The threshold was only accepted if the birds worked for two rewards following determination of a threshold. These factors strongly suggest that the results presented are true thresholds of colour perception for ducks and turkeys under these conditions.

In the present study, the operant-conditioning procedure used to train and test the birds employed a schedule of continuous reinforcement, where birds were rewarded after each correct response. This was because the software used to automate the operant apparatus was not programmed to allow any other schedule of reinforcement to be used. However, there is significant evidence in the literature that other schedules which intermittently reinforce correct responses after a set number or period of time, or both can have different effects on an animal's performance (for a review see Lattal, 1991). For example, variable-ratio schedules, where animals are reinforced after *n* responses and *n* varies each time, characteristically result in uniform response rates and the animal usually persists with the task whether a reward is provided or not (Ferster, 1960; cited by Mackay, 1991). Intermittent reinforcement with food also has advantages over continuous reinforcement as sessions are less likely to be limited in duration by the subject becoming satiated (McFarland, 1993). Thus, in future work a schedule of intermittent reinforcement of correct responses could be beneficial in training and testing birds for similar operant tasks, but this has not yet been assessed for ducks and turkeys.

The human subjects were literally, asked the same question as the birds. However, these subjects were not required to "prove" they could perceive the threshold they gave. The assumption that the volunteers would be truthful about what they could or could not see was made. The benefits of testing humans under the same conditions as the birds were twofold. Firstly, this enabled the method to be validated, by comparing the results for humans with previously published literature. As these are shown to be in good agreement with the results of similar tests, this indicates external validity of the method used. Secondly, the comparison is important because the experiment was intended to yield information that may be useful to improve the lighting and its measurement in poultry houses (see Chapter 4). As improvements must meet the needs of both the birds and stockpersons, it is important that comparisons of their vision under similar conditions are made.

3.5.3 Spectral sensitivity and its relation to avian ecology

Whilst this study shows that ducks and turkeys have the ability to perceive a wide range of wavelengths, extending from the UV_A (λ=360 nm) to red (λ=694 nm) ranges of the spectrum, it does not indicate how the birds use this visual ability. However, many

studies have attempted to correlate the predicted spectral sensitivity of birds with their ecology (Muntz, 1972; Lythgoe, 1979; Martin, 1985; Hart, 2001a; Hart, 2001b). The perception of a wide range of colours brings a number of advantages to a bird, and an increasing number of studies have shown that colour cues are used by avian species for a range of functions of biological relevance to birds. However, the functional significance of colour vision in some areas of the spectrum has yet to be determined (Honkvaara et al, 2002). For others, such as UV_A perception, several explanations have been suggested (Bennett and Cuthill, 1994; Derrington, 2002).

The ecological importance of UV_A vision in birds has mainly been studied in the context of social and sexual signalling, but recently the importance of UV_A vision in foraging has received more attention. Studies have shown it to enhance the ability of some birds to find seeds, berries and insects that reflect UV_A light (Burkhardt, 1982; Siitari et al, 1999; Siitari and Hovi, 2002). This would clearly be an advantage for birds such as fowl and turkeys which feed on a wide range of food items which are known to reflect UV_A light. However, ducks are less likely to benefit from this as their foraging habits do not require them to distinguish berries from foliage, and the majority of their food source is obtained from dabbling at the surface of the water for aquatic plants, invertebrates and algae (Owen and Black, 1990; McNeil et al, 1992), and up-ending to forage underwater. This feeding strategy is not dependent on visual cues since ducks tend to rely on taste rather than colour in food selection (Martin and Lett, 1985; cited by Jane, 1986). It is also unclear if dabbling ducks use vision underwater, although it is stated by Jane (1986) that they do not. The visual field of these birds is also a feature of birds that do not need to monitor the bill position when feeding, unlike fowl (Martin, 1986) (see Chapter 2, section 2.2.2.2).

UV_A vision may also be used for social signalling. Fowl are known to prefer potential mates that are illuminated with natural levels of UV_A (Jones et al, 1999; 2001). The feathers of fowl also are highly reflective of these wavelengths, whilst turkeys have been shown by Sherwin and Devereux (1999) to have markings that are visible under UV_A light, and it is suggested that these may play a role in social recognition and sexual selection. Such markings were not observed in fowl (Prescott and Wathes, 1999b), which may indicate this is a cue used by turkeys, but not fowl, and suggesting a function for their enhanced sensitivity to UV_A wavelengths. It is not known if the white plumage of domestic ducks reflects UV_A light, but the brown plumage of the pintail

(*Anas acuta*) and the white plumage of mute swans (*Cygnus olor*), species that have similar freshwater ecologies to wild mallard, have been shown to reflect minimal UV_A (Burkhardt, 1989; Finger and Burkhardt, 1993). It has also been suggested that mallard may use other colour cues to select potential mates. Omland (1996) found that female mallards select males with yellow-green bills preferentially to those with olive-grey bills, whilst variation in plumage characteristics such as the green head, neck rings and maroon breast seen in mallard drakes had no effect. Whether this character is correlated with other success factors (e.g. dominance status) is unknown. UV_A signalling may also allow birds to communicate with conspecifics through a channel of perception not available to some of their predators (Silerglied, 1979), as occurs in swordtail fish (*Xiphophorus nigrensis*) (Cummings et al, 2002). The benefits of this to prey species such as ducks and turkey would be considerable, if shown to be used.

Whatever the benefits of UV_A vision for these birds, it should not be considered more important to a bird than the ability to perceive any other colour. Although, studies have indicated its use in some visual tasks (Bennett and Cuthill, 1994) it may be no more useful than any of the other colours in the visual spectrum of these birds. However, more experimental evidence is required to assess how birds use wavelengths in the whole range of their visual spectrum.

3.5.4 Conclusions on the perceived spectral sensitivity of ducks and turkeys

The results of this study show that both ducks and turkeys have a broader and greater sensitivity than humans, particularly when compared to the CIE standard human spectral sensitivity curve (1983). This has a number of implications for these species when housed under artificial lighting (see section 3.1). As UV_A radiation is virtually absent from conventional artificial light sources, a lack of these wavelengths may deny these birds the use of visual cues transmitted by UV_A light that may be important to them. For example, if turkeys use the markings found in the plumage (Sherwin and Devereux, 1999) of other birds for social recognition then this capability and use of cues will be unavailable to these birds. Thus when reared under lighting of inappropriate colour balances, ducks and turkeys may be prevented from using their visual system to its fullest extent.

Another implication of a broader sensitivity extending into the UV_A range is that there may be an increase in perceived illuminance to that perceived by a human, particularly if the light contains a UV_A wavelength component. This would have major implications on how illuminance is measured for ducks and turkeys, particularly the illuminance of different types of light sources. This study implies that measuring illuminance using the lux unit may be inappropriate, and will misrepresent how these birds perceive their light environment. Additionally, studies that equate light sources and coloured light treatments using this unit will most certainly confound illuminance and colour in experiments with ducks and turkeys. As the spectral sensitivity of these two poultry species has now been determined in a way that accounts for the integrated processing of colour information by the retina and the visual neural pathways, it is now feasible to calculate estimates of duck and turkey perceived illuminance from different light sources, similar to what has been done for the domestic fowl (Prescott and Wathes, 1999a; 2003) (see Chapter 4).

Chapter 4:

Describing and Measuring the Light Environment in Duckling and Turkey Poult Housing

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4.1 Introduction

The majority of poultry in the UK are housed in environmentally controlled buildings in which artificial lighting is provided. The light environment in such housing is controlled in terms of illuminance, source, colour and photo-period to reduce aggression, injurious pecking, activity levels and energy costs, as well as to optimise production (Appleby et al, 1992). An estimated 90% of the turkeys produced for meat in the UK are reared in windowless housing with systems of environmental control (FAWC, 1995). A comparable proportion of ducks in the UK are reared in intensive housing, similar in most respects to buildings provided for other types of poultry (Cherry, 1993). These environmentally controlled houses have advantages over free range systems, since natural illuminance and day-length variations are not always suitable for year-round poultry production (Rose, 1997). Manipulations of the lighting in poultry housing results in birds being reared in light environments that are often controlled at levels which are markedly different from the natural light environments found in the natural habitats of the progenitor species of domestic poultry, and it has been suggested that this may contribute to the aetiology of some significant welfare problems (see Chapter 2, section 2.3).

In order to start to address the welfare issues associated with commercial lighting, it is necessary to detail and characterise the lighting practices and physical light environments that are commercially used. This has been done for a number of systems for domestic fowl reared in the UK, including reviews of some lighting practices by the Farm Animal Welfare Council (FAWC, 1991; 1992; 1997; 1998) and a survey of illuminances and spectral power outputs of typical lighting used in domestic fowl housing (Prescott and Wathes, 1999b). For turkeys the most comprehensive review of lighting practices in the UK is given in the FAWC Report on the Welfare of Turkeys (1995), whilst Grimes and Siopes (1999) have surveyed some aspects of typical light environments for turkey breeder housing in the USA. However, these reviews of lighting for turkeys are by no means complete in their description of the commercial

light environments used, and no studies describe in detail those used for domestic ducks. Based on these reviews for turkeys and domestic broiler fowl, the physical light environment of commercial poultry housing is described below in terms of the features that may affect the birds' behaviour, health, production and welfare.

The artificial light environment in poultry houses is different in quantity and quality to natural daylight, which is presumably optimal for the efficient functioning of the visual system of fowl, ducks and turkeys. Firstly, the illuminances in poultry housing are usually maintained at very low levels. Table IV.1 in Appendix IV gives the typical illuminances encountered in various natural and artificial light environments to illustrate this. Typical illuminances in turkey housing have been reported as being between 20 and 25 lux for the first few days of brooding, reducing to 1 to 4 lux during the rest of rearing (FAWC, 1995). However, much lower illuminances (1 lux and less) are known to be used to control outbreaks of aggression and injurious pecking in turkeys (Moinard et al, 2001). In broiler and laying hen housing, mean illuminances of approximately 3 and 20 lux, respectively, are reported (Prescott and Wathes, 1999b). The variation in illuminance around a poultry house in the Prescott and Wathes (1999b) survey also was found to be large when birds were kept at different levels in a house (between 1.6 and 270 lux in a caged hen house depending on distance of cage from the light source), whilst in housing for birds on a single level, as for broilers and other meat birds, the variation was much less (Prescott, 1999; Prescott and Wathes, 1999b).

Secondly, the artificial light sources used in poultry housing may be incandescent, fluorescent or compact fluorescent luminaires, which are usually described as "white" light sources. However, these each produce light which has a different relative spectral power distribution to natural daylight (Prescott and Wathes, 1999b; Prescott et al, 2003), and thus also have markedly different colour temperatures. (see Appendix IV for a brief explanation of colour temperature and Table IV.2 for the colour temperatures of a range of light sources for comparison). Daylight has a relatively even distribution of wavelengths between 400 and 700 nm, with UV_A radiation (315 to 380 nm) becoming progressively attenuated as wavelength shortens. In natural environments the colour balance of daylight varies over the course of a day (particularly at dawn and dusk), but it is also subject to obstruction from clouds and is dependent on light transmission through foliage and reflection from other surfaces (Endler, 1993; Endler and Thery, 1996). In contrast, artificial lighting commonly used in poultry housing emits little or no

UV_A radiation. Incandescent light contains an abundance of red wavelengths, whilst the wavelength composition of fluorescent lights depends on the phosphor mixes used to line the inside of the tube, which is responsible for producing visible light. Other light sources, such as high-pressure sodium lamps are reported to be commonly used in turkey breeder housing in the USA (Grimes and Siopes, 1999), but their use is not widely reported for poultry in the UK (Prescott et al, 2003).

Finally, the photoperiod used in poultry housing may be very different to that encountered in natural light environments. In general, poultry species reared for meat are given much shorter periods of darkness than occurs naturally. This can vary from no dark period, or a very short dark period such as 1 h, to longer periods of any duration up to 12 h. Many poultry producers are now starting to use longer durations of darkness, as these have been shown to have benefits, such as higher feed conversion ratios, fewer leg and eye problems and lower mortality, compared with continuous lighting (Classen, 1991; Gordon and Tucker, 1997). Intermittent lighting systems, which provide more than one dark period in every 24 h, are also used commercially. The duration of light may also be stepped-up (increased) or stepped-down (decreased) over the production cycle (Nixey, 1994). In many poultry houses, the transition between the light and dark periods of the photoperiod is usually abrupt. Recommendations for dawn and dusk periods (RSPCA, 1999a; 1999b; 1999c; 1999d; Council of Europe, 1995; 1999; 2001) (see Chapter 2, Table 2.3) are sometimes incorporated into lighting programmes, to enable birds to prepare for the onset of a dark or light period. In addition, the dark periods in poultry housing usually consist of complete darkness, whereas in natural environments a certain amount of illumination would occur from the moon or starlight.

Of the aspects of the light environment mentioned above, illuminance is the only parameter that requires direct measurement. The details of the photoperiod regime and type of light sources used can be easily recorded by the experimenter or gained from the personnel managing commercial poultry units. The spectral power distributions of the light sources used may be measured if access to the appropriate equipment (i.e. a spectroradiometer) is available. Alternatively, spectral emission data may be obtained from the lamp manufacturers (Lewis and Morris, 2000). Illuminance (the amount of light falling on a surface per unit area) is often measured in the lux unit using light meters. The lux is a photometric unit calculated from the spectral power distribution of a light source and the spectral sensitivity of the human. This has implications for

measuring illuminance as perceived by animals with a different spectral sensitivity to humans (see Chapter 3).

As illuminance reduces exponentially with distance from a light source, it is important that a sufficient number of measurements are made at appropriate levels so as to accurately reflect the variation in illuminance within a building or pen. Standard methods for sampling illuminance in buildings have been published (IES, 1966). In single level poultry housing, such as that used for meat birds, illuminance is measured either at a stated level from the floor (Prescott and Wathes, 1999b) or at the eye height of the birds (Thompson, 2001; FAWC, 1995). Where the source of lighting employed is of a single type and lamps are evenly spaced throughout a building, transects across the housing area need only be made directly below and between the rows of lights. However, where lights are of different types or unevenly spaced more transects of readings will be required (Prescott and Wathes, 1999b; 2003).

The orientation of the sensor head is also very important (Prescott et al, 2003). In the literature concerning lighting for poultry, three methods are described for the orientation of the light meter sensor. In the first method, the sensor is held on the horizontal plane (Kjaer and Vestergaard, 1999; Moinard et al, 2001). In the second, the sensor is angled in the direction of maximum illuminance, i.e. towards the nearest light source (Lewis et al, 1999; Prescott and Wathes, 1999b). The third method is that recommended by The Standing Committee of the European Convention on the Protection of Animals Kept for Farming Purposes, and involves taking measurements on three planes at right angles to each other (Council of Europe, 1995; 2001). The difference in the readings that these methods generate can be significant, for example, Prescott et al (2003) obtained a reading of 74 lux when holding a light sensor horizontally, and 114 lux when it was angled in the direction of maximum illuminance, when held at a position 1.5 m on the floor from the point directly under an incandescent bulb. The best method of orientating the sensor for measuring illuminance in poultry housing has not been determined, but due to the variation between the above methods, it is clearly important to state which is used when detailing illuminance measurements in poultry housing.

The review of literature and lighting recommendations in Chapter 2 (sections 2.3 and 2.4) highlights that there is a requirement for accurate descriptions and measurements of the light environment for poultry, both experimentally and commercially, with the use

of calibrated equipment and trained personnel. In previous surveys and experimental research, the lighting environment or treatments used are often only partially described in terms of source, photoperiod, wavelength or illuminance. Additionally, the use of the lux unit is questionable for measuring illuminance perceived by poultry (Nuboer et al 1992; Prescott and Wathes, 1999a). As shown in Chapter 3, the spectral sensitivity of domestic ducks and turkeys differs from that of the CIE standard human photopic spectral sensitivity curve (1983), which is used in the calculation of the lux measurements. These findings indicate that the lux unit will be inappropriate for measuring illuminance as it is perceived by these birds. The measurement of fowl-perceived illuminance in, in the *c*lux (Prescott and Wathes, 1999a) and galluminance units (Nuboer et al, 1992) has been proposed. With the spectral sensitivity of ducks and turkeys determined by a behavioural test (Chapter 3) it is now also possible to calculate estimates of illuminance as perceived by ducks and turkeys.

4.2 Aims and objectives

The aim of the investigations detailed in this chapter were firstly, to undertake a survey to characterise the light environments used in commercial duck and turkey poult houses by defining the light sources, photoperiods, illuminances and spectral power outputs of typical lighting used by producers in the UK. Secondly, to use the spectral power outputs of commercially used lighting and the spectral sensitivity data determined in Chapter 3 to calculate estimates of the perceived illuminance from these light sources for domestic ducks and turkeys.

4.3 Materials and methods

4.3.1 A survey of the light environment in duckling and turkey poult houses

Four major duck and four major turkey producers in the UK were approached to participate in a two-part survey to quantify the characteristics of the typical light environments for duckling and turkey poult housing employed on their farms. The producers who participated are roughly estimated to produce 70% of all duck and turkey meat in the UK (see section 4.5.1 for further details). The survey consisted of a questionnaire that was completed with the farm managers, and measurements made of the lighting environments within the houses surveyed. Visits were made to a number of

houses on different farm sites for each producer, to represent the various types of housing, lighting systems and management practices used. In total 19 duckling and 16 turkey poult houses were surveyed. Houses with similar layouts and types of light source, but containing birds of differing ages between 1-49 days old were surveyed to reflect any changes made to the light environment during the production cycle. Where possible at least two houses with similar types of light source, layout and age of birds were sampled as replicates; although this was not always possible, as not all producers had similar houses containing birds of the same age.

4.3.1.1 Questionnaire of light practices and management

The questionnaire addressing issues of lighting practices and management was completed with the farm managers/personnel for each house surveyed (see Tables 4.1 and 4.2). This comprised of 10 questions designed to ascertain the type of lighting, duration and methods of measuring illuminance used by the producers. The questionnaire also invited the managers to estimate the perceived level of illuminance within the houses and comment on the level of satisfaction that they had with their lighting practices. Responses to the questionnaire were later collated, and the percentage of the houses surveyed giving each response was calculated.

4.3.1.2 Light measurements

Two parameters of the light environment were measured within each house surveyed: the range of illuminances within the house and the spectral power distributions of the light sources installed. The illuminance in the houses was measured at 0.20 m above floor height by angling the sensor of a calibrated light meter (Model 545, Testo Ltd., Alton, UK) in the direction of maximum radiance, as described by Lewis et al (1999) and Prescott and Wathes (1999b). Measurements were made to the nearest lux, thus readings of 0.5 – 1.49 lux were rounded to 1 lux and readings <0.49 were rounded to 0 lux. In houses where the light source was of a single type and fittings were regularly spaced, illuminance measurements were made at 9 locations approximately 2 m apart along transects of the building directly beneath and between rows of luminaires. In housing where different types of light sources were used additional transects of measurements were made to reflect the greater variation in illuminance resulting from this. The measurements made were collated, and the minimum, maximum, mean and standard deviation of illuminance for the individual houses surveyed, and for all of the houses for each species were calculated.

Measurements of the spectral power distributions of two representative lamps for each light source installed within the houses were made using a calibrated spectroradiometer Model ST2000, Ocean Optics Inc., Dunedin, Florida, USA). The sensor of the spectroradiometer was attached to an extendable measuring pole (Digirod, RS Components Ltd, Corby, Northants, UK) so that it could be held as close to the lamps as possible to obtain a reading. The height of the lamps from the floor was also measured at this point, using the measuring pole, which was calibrated to give a digital reading of the length it was extended plus its 1.5 m unextended length. In addition to these measurements, the spectral power distribution of daylight outside each house was also recorded if the house was found to admit daylight. The spectral data collected during the survey were later collated into Microsoft Excel '97 spreadsheets and converted from $\mu W\ cm^{-2}\ nm^{-1}$ to the relative percentage spectral power contributions at different wavelengths (% of total power output) for each light source.

4.3.2 The calculation of perceived illuminance for ducks and turkeys

The spectral power distribution data collected during the survey was integrated with the spectral sensitivity data obtained in Chapter 3, to allow the estimation of illuminance as perceived by ducks and turkeys. The method used to calculate these duck and turkey perceived illuminances was similar to that used by Prescott and Wathes (1999a) to derive the *c*lux unit for domestic fowl.

The spectral power distributions ($\mu W\ cm^{-2}\ nm^{-1}$ at 5 nm intervals between 300 and 700 nm) of the eight types of artificial light sources measured in the duck and turkey houses, and of daylight, were collated into a Microsoft Excel '97 spreadsheet along with the data of the CIE standard human photopic spectral sensitivity curve (1983) at the same intervals. First, the spectral power distribution (SPD) data for each light source was converted into a photon flux (PF) for each 5 nm interval. This was done because electromagnetic radiation that produces a visual response (visible light) is usually referred to in terms of PF when dealing with biological systems (Loew, 1999). However, in photometry and physics it is traditionally expressed as radiant power (usually in Watts). Regardless of which of these units is used, the results will be equivalent as radiant power can be converted into a PF and *vice versa*. A series of calculations were then made to convert the PF data of the light sources into a standardised spectral power distribution (SSPD) for these light sources, when made iso-

luminant (of equal brightness), with reference to the CIE standard human spectral sensitivity curve (1983). These iso-luminant SSPD data were then multiplied by the relative spectral sensitivity data for the duck and turkey (at 5 nm intervals; as read from the curves shown in Figure 3.11 in Chapter 3). This was to obtain the equivalent light level perceived by ducks and turkeys when the light sources were iso-luminant, with reference to the CIE standard human spectral sensitivity curve (1983). Using these values it was then possible to determine ratios of how a duck or turkey perceives each light source, compared to its illuminance measured in lux. The appropriate ratios were then applied to a selection of the illuminance measurements (lux) taken from the different light sources in the survey and used to convert them to a corrected unit for the illuminance perceived by the birds. These calculations assume some similarity of the maximum spectral luminous efficacy between species, which is discussed further in section 4.5.2. The data were also used to calculate a ratio of how these birds perceive one light source compared to another when they are isoluminant, as measured in lux units. The full procedure for calculating the alternative units/correction factors is given in Appendix V.

The above method for calculating the duck and turkey perceived illuminances was also followed using the spectral sensitivity data for the human that was determined in Chapter 3. This was undertaken for comparative purposes, as the CIE standard human photopic spectral sensitivity curve (1983) is an amalgam of various data derived under various light conditions.

4.4 Results

4.4.1 A survey of the light environment in duckling and turkey poult houses

4.4.1.1 Questionnaire of lighting practices and management

Summaries of the responses to the questionnaire are provided in Tables 4.1 and 4.2. All responses were from farm managers/personnel representing the commercial duck and turkey producers visited, with one response per house surveyed.

The survey showed that a wider range of artificial light source types were used in the duckling houses, compared to in turkey housing. Of the 19 duckling houses surveyed, 31.6% were installed with incandescent light sources (see Table 4.1). The same

Table 4.1 A summary of the responses from four major duck producers to the questionnaire on lighting practices and management employed in 19 houses for ducklings between 1 and 49 days of age.

Question	Response	% of Houses
1. What type (source) of artificial lighting is used in the houses that were surveyed?	Incandescent. Fluorescent. Compact fluorescent. Mix (incandescent and fluorescent).	31.6 31.6 26.3 10.5
2. What are the reasons for using the type of artificial lighting in the houses?	Company policy. Individual farm manager's choice.	52.6 47.4
3. Do you admit daylight into your houses? If so, why?	Yes, for ventilation purposes. No.	47.4 52.6
4. What age are birds when daylight is admitted?	1 day. 14 days. Never.	10.5 36.8 52.6
5. What photoperiods are employed?	- 1-14d = 23L:1D; 14-28d = ½hr daily reduction in light; 28-49d = 17L:7D. - 1-49d = 23L:1D. - 1-49d = 24L.	21.1 68.4 10.5
6. Is a dawn/dusk system used?	Yes. No.	- 100

Table 4.1 (cont.) A summary of the responses from four major duck producers to the questionnaire on lighting practices and management employed in 19 houses for ducklings between 1 and 49 days of age, continued.

Question	Response	% of Houses
7. How often is a light meter used to measure illuminance/ intensity in the houses?	Never. Occasionally (less than once per flock). At least once per flock.	21.0 79.0 -
8. Are you satisfied with your lighting system?	Yes No	89.5 10.5
9. If no, what changes would you make?	Incorporate timers into the lighting circuits.	10.5
10. Further comments	What are the light intensity requirements for ducks? Would consider making changes to meet supermarket/welfare standards.	

Table 4.2 A summary of the responses from four major turkey producers to the questionnaire on lighting practices and management employed in 16 houses for turkey poults between 1 and 49 days of age.

Question	Response	% of Houses
1. What type (source) of artificial lighting is used in the houses that were surveyed?	Incandescent. Fluorescent. Compact fluorescent. Mix (incandescent and fluorescent).	87.5 12.5 - -
2. What are the reasons for using the type of artificial lighting in the houses?	Company policy. Individual farm manager's choice.	62.5 37.5
3. Do you admit daylight into your houses? If so, why?	Yes. No.	- 100
4. What age are birds when daylight is admitted?	N/A	-
5. What photoperiods are employed?	- 1-3d = 23L:1D; 3-49d = 16L:8D. - 1d = 23L:1D; 2-8d = 1hr daily reduction in light; 8-49d = 16L:8D. - ♂1-3d = 24L; 3-13d = 1hr daily reduction in light; 14-49d = 14L:10D (15min gradual dimming of light); ♀1-3d = 24L; 3-11d = 1hr daily reduction in light; 12-49d = 16L:8D (15min gradual dimming of light). - ♂1-3d = 24L; 3-13d = 1hr daily reduction in light; 14-49d = 14L:10D; ♀1-3d = 24L; 3-11d = 1hr daily reduction in light; 12-49d = 16L: 8D. - ♂1-3d = 21L:3D; 4-7d = 19L:5D; 8-49d = 16L:8D; ♀1-3d = 21L:3D; 4-49d = 19L:5D.	12.5 25.0 12.5 25.0 25.0

Table 4.2 (cont.) A summary of the responses from four major turkey producers to the questionnaire on lighting practices and management employed in 16 houses for turkey poults between 1 and 49 days of age., continued.

Question	Response	% of Houses
6. Is a dawn/dusk system used?	Yes. No.	12.5 87.5
7. How often is a light meter used to measure illuminance/ intensity in the houses?	Never. Occasionally (less than once per flock). At least once per flock.	25.0 50.0 25.0
8. Are you satisfied with your lighting system?	Yes. No.	100 -
9. Is beak trimming practised?	Yes. No.	43.8 56.2
10. Further comments	Would consider making changes to meet supermarket/welfare standards. Would like to perform trials with blue and green coloured lights.	

percentage of duckling housing used conventional fluorescent light sources, with compact fluorescent lamps (26.3%) and mixes of incandescent and conventional fluorescent lamps (10.5%) also being employed. In comparison, the majority of turkey houses (87.5%) were illuminated with incandescent lighting, with only 12.5% using conventional fluorescent lamps (see Table 4.2). For 47.4% of the duckling houses and 37.5% of turkey poult houses, the decision about the light source type used was made by individual farm managers and for the remainder was dictated by company policy. No coloured luminaires or filters were used in any of the duckling or turkey houses surveyed. However, as shown in the further comments section of Tables 4.1 and 4.2, some personnel from the turkey producers did express an interest in performing production trials using blue and green coloured lighting in the future.

Less than half of the duckling houses surveyed (47.4%) used natural daylight (questions 3 and 4, Tables 4.1 and 4.2). Of those that did allow daylight to enter the houses, 36.8% only did so from 14 days onwards; after the ducklings had been brooded. This was a consequence of the partially open-sided housing used for ventilation reasons rather than an overt choice for natural lighting. None of the turkey poult houses surveyed admitted daylight during brooding (usually up to 49 days).

The majority of duckling houses (68.4%) used a 23L:1D photoperiod for all of the rearing period (usually up to 49 days). Approximately 21% of the houses employed a step-down regime after the brooding period, where there was a daily reduction of the light period until a photoperiod of 17L:7D was reached, and then maintained until the end of rearing. In 10.5% of the duckling houses, no dark period was provided. The reason given for this was that no timers were incorporated into the lighting systems for these particular houses (question 9, Table 4.1). A larger range of different photoperiods were employed in the turkey poult houses, as dictated by company policies. Turkey producers provided their birds with substantially longer periods of darkness (5 h or more) than was provided in most duckling houses surveyed. The responses to question 5 in the questionnaire showed that the photoperiod in all of the turkey houses was changed over the course of the production cycle to provide longer periods of darkness as the birds aged. In 62.5% of the houses a distinction between the photoperiods for male and female birds was made, with shorter dark periods for females used than for males. The practice of providing a dawn/dusk period for ducks and turkeys was uncommon;

being incorporated into the lighting regime for only 12.5% of the turkey houses surveyed.

The responses to question 7 showed that whilst light meters were used by producers, they were only used on an occasional basis (less than once per flock) in the majority of duckling (79.0%) and turkey (50%) houses. Light meters were never used in 21% duck and 12.5% of turkey houses. However, many farm managers/personnel confirmed verbally that they had been provided with guidelines, often in the form of marks made on dimmer switches, as to the approximate settings for the level of illuminance within the houses they managed. Additionally, farm managers were requested to estimate the illuminance of the houses surveyed, and these estimates are shown in Tables 4.3 and 4.4, alongside the illuminance measurements taken. The results of these estimates are compared to the results of the illuminances measured in section 4.4.1.2 Light measurements.

Most duck and turkey producers indicated that they were satisfied with their current lighting systems and practices, although 10.5% duckling farm managers reported a wish to install time clocks in their lighting circuits. Some showed an interest in the illuminance requirements of ducks; whilst others indicated that they would consider making changes to their lighting practices if supermarket / welfare standards required it.

4.4.1.2 Light measurements

Tables 4.3 and 4.4 show the illuminances measured in the duckling and turkey houses surveyed. These illuminances were much lower than for daylight, which can range up to 100,000 lux. The variation in illuminance within the duckling houses was greatest in the partially open-sided buildings, which admitted daylight. This style of housing was most commonly used for birds after their initial 14-21 day brooding period, thus accounting for the increased illuminances measured in such housing containing older birds. Within the light-controlled duckling buildings, the variation in illuminance was much less, and changed little over the birds' production cycle. The exception to this was duck producer 1, who decreased the illuminance in the houses after 14 days.

In general, the illuminances measured in the turkey poult houses (mean of all turkey poult houses=5.3 lux, s.d=2.43) were lower than those recorded in the duckling houses (mean of all duckling houses=22.6 lux, s.d=13.82). The highest illuminances and

Table 4.3 The illuminance measurements and estimates recorded in the housing of four major duck producers for ducklings between 1 and 49 days of age.

Producer	House	Housing type	Lighting type	Age (days)	Managers estimate of mean illuminance (lux)	Measured illuminance (lux)				
						Min.	Max.	Mean	sd	n
1	1	Light controlled	IN 60W; GEC, Pearl	1-14	5	1	10	4.2	3.15	18
	2	Light controlled	IN 60W; GEC, Pearl	1-14	5	1	13	5.4	3.94	18
	3	Light controlled	IN 60W; GEC, Pearl	14-49	<5	0	3	1.3	0.84	18
	4	Light controlled	IN 60W; GEC, Pearl	14-49	<5	0	3	1.11	1.08	18
2	5	Light controlled	IN 60W; GEC, Pearl + FL[t]; 20W; Osram	1-14	20	5	27	16.7	7.20	18
	6	Light controlled	IN;60W; GEC, Pearl + FL[t]; 20W; Osram	14-49	20	6	30	14.3	7.21	27
	7	Partially open sided	IN 60W; GEC, Pearl + daylight	1-21	>20	23	241	86.7	82.98	18
	8	Partially open sided	IN 60W; GEC, Pearl + daylight	21-49	>20	27	261	92.9	83.90	18
3	9	Partially open sided *	FL[c] 11W; Phillips	1-14	10-20	5	23	9.9	4.43	27
	10	Partially open sided *	FL[t] 11W; Phillips	1-14	10-20	5	20	9.8	4.14	27
	11	Partially open sided	FL[t] 11W; Phillips + daylight	14-49	40	20	49	32.3	10.05	18

Table 4.3 (cont.) The illuminance measurements and estimates recorded in the housing of four major duck producers for ducklings between 1 and 49 days of age, continued.

Producer	House	Housing type	Lighting type	Age (days)	Managers estimate of mean illuminance (lux)	Measured illuminance in (lux)				
						Min.	Max.	Mean	sd	n
3	12	Partially open sided *	FL[c] 11W; Phillips	1-14	10-20	5	13	7.5	2.15	18
	13	Partially open sided *	FL[c] 11W; Phillips	1-14	10-20	4	12	7.3	2.25	18
	14	Partially open sided	FL[c] 11W; Phillips + daylight	14-49	40	20	43	31.9	7.99	18
	15	Partially open sided	FL[c] 11W; Phillips + daylight	14-49	40	21	47	32.1	8.46	18
4	16	Light controlled (new style)	FL[t] 40W; GEC	1-49	No estimate	6	31	15.0	6.64	27
	17	Light controlled (new style)	FL[t] 40W; GEC	1-49	No estimate	7	27	14.0	5.91	27
	18	Light controlled (older style)	FL[t] 40W; GEC	1-49	No estimate	9	49	24.9	11.73	27
	19	Light controlled (older style)	FL[t] 40W; GEC	1-49	No estimate	10	39	22.4	8.52	27
Mean						**9.2**	**49.5**	**22.6**	**13.82**	

IN = Incandescent bulbs, FL[t] = Fluorescent tubes, FL[c] = Compact Fluorescent bulbs; * These houses had their sides boarded since at the time of recording the ducklings were less than 14 days of age and being brooded.

Table 4.4 The illuminance measurements and estimates recorded in the housing of four major turkey producers for turkey poults between 1 and 49 days of age.

Producer	House	Housing type	Lighting type	Age (days)	Managers estimate of mean illuminance (lux)	Measured illuminance				
						Min.	Max.	Mean	sd	n
1	1	Light controlled	IN 100W; GEC, Pearl	3-21	10	1	6	3.3	1.53	18
	2	Light controlled	IN 100W; GEC, Pearl	21-49	20	9	52	30.6	14.33	18
2	3	Light controlled	IN 100W; GEC, Pearl	1-49	3-4	1	3	2.8	0.67	18
	4	Light controlled	IN 100W; GEC, Pearl	1-49	3-4	1	3	2.2	0.65	18
	5	Light controlled	IN 100W; GEC, Pearl	1-49	3-4	1	5	2.4	1.15	27
	6	Light controlled	IN 100W; GEC, Pearl	1-49	3-4	1	6	2.7	1.48	27
	7	Light controlled	FL^t 20W; Osram	1-49	5-6	2	10	5.4	2.10	27
	8	Light controlled	FL^t 20W; Osram	1-49	5-6	1	8	5.0	2.08	27
3	9	Light controlled	IN 60W; GEC, Pearl	4-7	>5	1	16	5.4	5.24	18
	10	Light controlled	IN 25W; GEC, Pearl	8-35	>5	3	13	6.9	2.92	18
	11	Light controlled	IN 25W; GEC, Pearl	36-38	>5	4	11	7.1	1.78	18
	12	Light controlled	IN 25W; GEC, Pearl	39-49	<5	2	7	4.3	1.60	18

Table 4.4 (cont.) The illuminance measurements and estimates recorded in the housing of four major turkey producers for turkey poults between 1 and 49 days of age, continued.

Producer	House	Housing type	Lighting type	Age (days)	Managers estimate of mean illuminance (lux)	Measured illuminance				
						Min.	Max.	Mean	sd	n
4	13	New, light controlled	IN 60W; Marathon, Pearl	8-49	1-5	1	4	1.6	0.92	18
	14	New, light controlled	IN 60W; Marathon, Pearl	8-49	1-5	1	3	1.4	0.70	18
	15	Old, light controlled	IN 60W; Marathon, Pearl	8-49	1-5	1	4	1.9	0.99	18
	16	Old, light controlled	IN 60W; Marathon, Pearl	8-49	1-5	1	3	1.7	0.75	18
Mean						**1.9**	**9.6**	**5.3**	**2.43**	

IN = Incandescent, FL[t] = Fluorescent tube luminaires

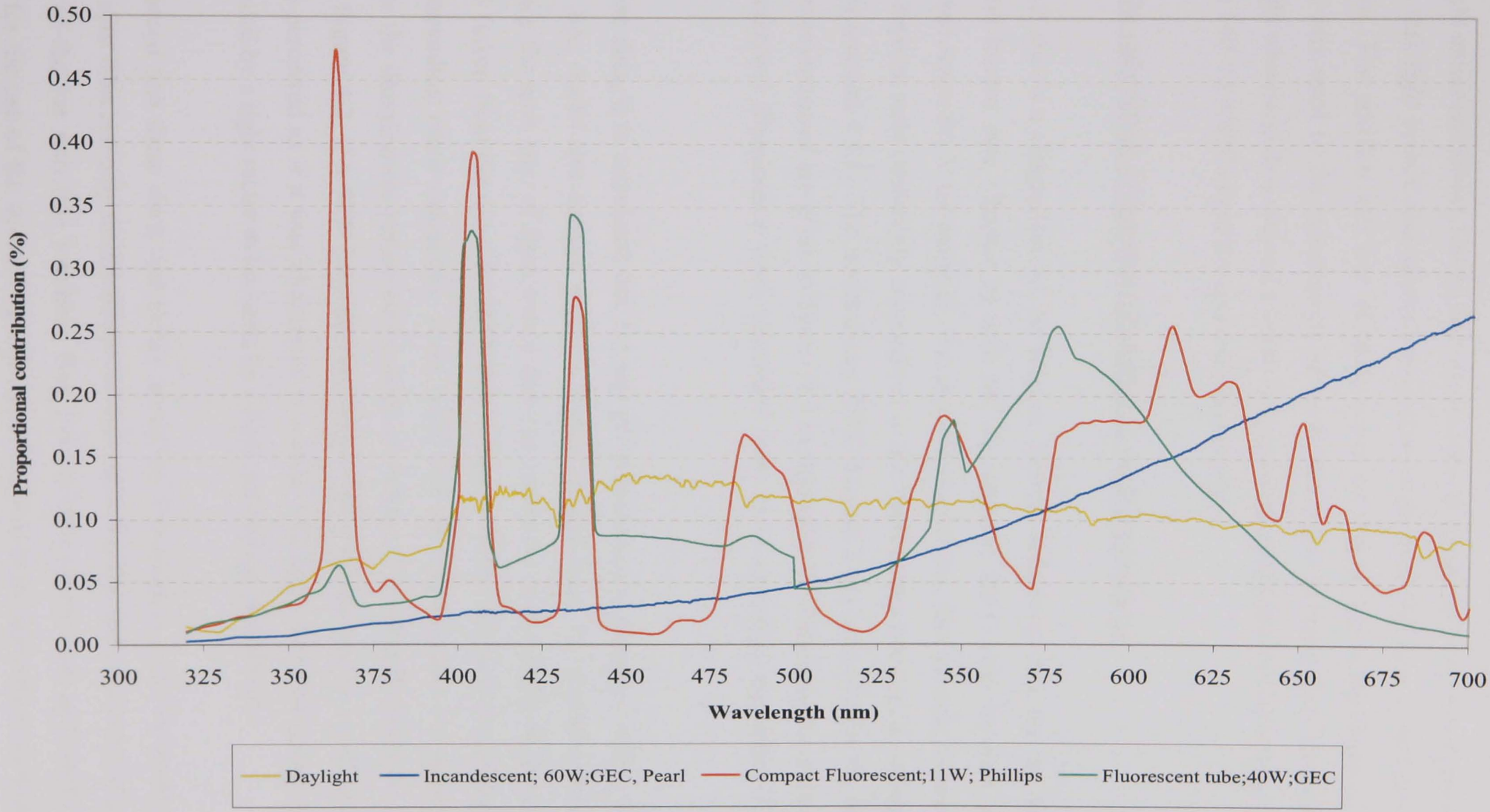
greatest variation was noted for producer 1. After the turkeys had been beak-trimmed, this producer later raised the illuminance for birds at 21 days of age. The three remaining producers (2, 3 and 4) did not make such changes to the levels of illuminance during the birds' production cycle, as observed in this survey until 49 days. Producer 4 did not beak-trim their birds and therefore used lower illuminances to control feather pecking and cannibalism. Producer 2 beak-trimmed all birds, and had a company policy of keeping illuminance as close to 5 lux as possible, given the need to control feather pecking and the capabilities of the lighting system used in the houses. Whilst the turkey producers surveyed had company policies to maintain illuminance at certain levels, it was largely accepted that farm managers would lower illuminance as necessary to prevent or control injurious pecking and aggression in the flocks.

A comparison of the farm managers/personnel estimates for the illuminance of the houses to the measurements taken showed that many were able to provide a reasonable estimate of the perceived illuminance in the houses. No estimates were obtained for duck producer 4, as the personnel declined to provide them. However, it was usual for overestimates to be made for those houses lit at lower illuminances (<20 lux) and to underestimate those houses lit at higher illuminances (>20 lux).

Although eight different artificial light source types were measured in the duckling and turkey poult housing (see Tables 4.3 and 4.4), the relative spectral power distributions of the different incandescent lamps and fluorescent tubes were all approximately similar. Therefore, for ease of presentation, only the relative spectral power distributions for a 60W incandescent bulb (GEC, Pearl) and 40W fluorescent tube (GEC) are compared in Figure 4.1, along with data for an 11W compact fluorescent bulb (Phillips) and daylight. These were the most commonly encountered light sources in the survey. Measurements of daylight were made for comparative purposes, and because it was an additional light source used in some duck housing.

In comparison to daylight, the incandescent luminaire provided much less UV_A radiation ($315 < \lambda < 400$ nm) but more red light ($630 < \lambda < 700$ nm), and was also depleted in blue wavelengths. The fluorescent tube showed a characteristic emission spectrum with maximum peaks at λ=405 nm, λ=435 nm, λ=545 nm and λ=580 nm. The compact fluorescent luminaire showed a spikier emission spectrum, and shared all but

Figure 4.1 Relative spectral power distributions for four light sources encountered in duckling and turkey poult houses



the latter of these peak wavelength emissions shown for the fluorescent tube, to greater or lesser proportions. In addition, this light source also showed the latter of these peak wavelength emissions shown for the fluorescent tube, to greater or lesser proportions. In addition, this light source also showed maximum peaks at λ=365 nm, λ=480 nm and λ=610 nm. The position and size of these peaks are due to the composition of the phosphor mix used in the manufacture of these two types of fluorescent luminaires. These light sources both contained a higher proportional contribution of wavelengths in the range $540 < \lambda < 630$ nm of the spectrum than daylight.

4.4.2 The calculation of perceived illuminance ducks and turkeys

Figure 4.2 shows a comparison of the relative spectral sensitivity data for the duck, turkey and human (see Chapter 3) with the iso-luminant SSPD data for four light sources (see Appendix V for method). For ease of presentation, data are only shown for the light sources most commonly encountered in duck and turkey housing, as shown in the survey (section 4.4.1). The iso-luminant SSPD data (at 5 nm intervals) for the other light sources measured are given in Table VI.1 in Appendix VI. Estimates for duck and turkey perceived illuminance were calculated from these data (see Appendix V for method).

From these data, it is calculated that for any given illuminance measured with a light meter in lux, ducks and turkeys perceive higher illuminances. To illustrate this, an illuminance for each type of light source that was measured in the survey is shown in Table 4.5 (taken from the mean for individual houses in Tables 4.3 and 4.4), alongside the corresponding ratios calculated. These were then used to calculate the examples shown for the illuminances perceived by ducks or turkeys. For example, from the data given in Figure 4.2, if a 60W incandescent lamp (GEC) was measured at 100 lux, it would be perceived as if it was illuminated at a level 1.83 and 1.80 times greater than that recorded by a light meter in lux units by a duck and turkey, respectively.

It is proposed that these duck and turkey perceived illuminances could be known as *d*lux and *t*lux. This not only differentiates the units from the lux, but retains the original meaning of the lux unit (the luminous flux from a light source per unit area) and accounts for the use of the spectral sensitivity of the birds in its calculation; as done in the naming of the *c*lux unit for domestic fowl (Prescott and Wathes, 1999a).

Figure 4.2 A comparison of the relative spectral sensitivity of the duck, turkey and human with the iso-luminant standardised spectral power distributions for four light sources encountered in duckling and turkey poult houses (the standardised spectral power distributions are iso-luminant with reference to the CIE (1983) standard human spectral sensitivity data).

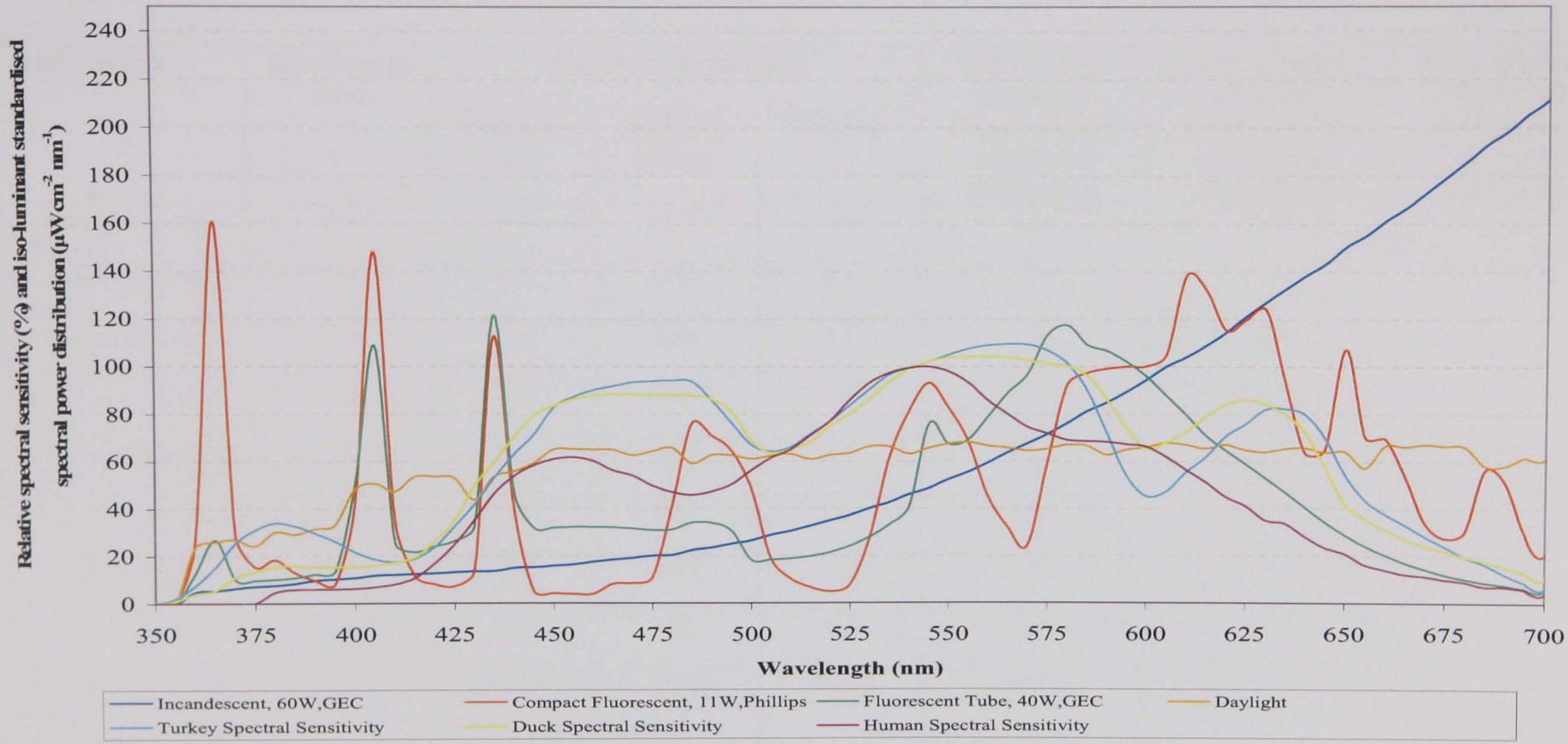


Table 4.5 Examples of the illuminance perceived by domestic ducks, domestic turkeys and humans of radiation from various light sources found in duckling and turkey poult housing, and daylight. The ratios of perceived illuminance to that measured in lux were used as correction factors to obtain the alternative units are shown. The illuminance measurements of the light sources (in lux) are taken from Tables 4.3 and 4.4.

Light Source	Illuminance (lux)	Perceived illuminance			Ratio of duck perceived illuminance to measured illuminance	Ratio of turkey perceived illuminance to measured illuminance	Ratio of human perceived illuminance to measured illuminance
		Domestic duck	Domestic turkey	Human			
60W incandescent lamp (GEC, Pearl)	5.4	9.9	9.7	6.6	1.83	1.80	1.22
100W incandescent lamp (GEC, Pearl)	2.8	5.1	5.0	3.4	1.83	1.81	1.23
25W incandescent lamp (GEC, Pearl)	6.9	12.6	12.4	8.3	1.83	1.80	1.21
60W incandescent lamp (Marathon)	1.6	2.9	2.9	1.9	1.83	1.80	1.21
11W Compact Fluorescent lamp (Phillips)	7.3	12.4	12.1	8.7	1.70	1.65	1.19
40W Fluorescent tube (GEC)	15.0	23.6	22.8	17.4	1.57	1.52	1.16
11W Fluorescent tube (Phillips)	9.9	15.1	14.7	11.3	1.53	1.48	1.14
20W Fluorescent tube (Osram)	5.0	8.3	8.1	6.2	1.65	1.61	1.23
Daylight – at 13:00 BST in August under sunny (some cloud) sky conditions	21,798	40,762	40,762	29,645	1.87	1.87	1.36

The calculations made in this study also indicate that ducks and turkeys will perceive the light sources measured to be of different brightness when they are illuminated to the same lux unit. This is illustrated in Table 4.6, which shows the illuminances perceived by domestic ducks and turkeys when the various light sources measured are isoluminant at 100 lux, calculated using the ratios shown in Table 4.5. This table also gives the ratios which can be used as the correction factors that the other light sources each need to be adjusted by, so they are perceived as isoluminant to a 60W incandescent (GEC) lamp by the duck or turkey. For example, the ratio of the illuminance perceived for a 60W incandescent (GEC) lamp to that perceived for a 40W fluorescent tube is 1.17 and 1.19 for ducks and turkeys, respectively. Therefore, when the incandescent lamp is lit at 100 lux a 40W fluorescent tube (GEC) may need to be lit at approximately 117 lux for ducks, and approximately 119 lux for turkeys for these birds to perceive them as isoluminant. According to the data in this study the illuminance from an incandescent lamp will be perceived by ducks to be approximately 17% greater than that perceived from a fluorescent tube lit to the same lux unit, and approximately 19% greater by turkeys.

Of the light sources measured, daylight was the only type to be perceived by the birds to be of higher illuminance than the 60W incandescent (GEC) light source. The latter was selected for others to be compared to, as it was the most commonly encountered type used in the duckling and turkey poult housing surveyed.

These results indicate that the illuminances perceived by domestic ducks and turkeys, for the light sources measured, are very similar. In comparison, humans perceived a lower illuminance than the birds. Estimates of perceived illuminances for the human have been calculated, and are given in Tables 4.5 and 4.6. However, although these results seem to indicate that humans will also perceive the illuminance from these light sources to be greater than that measured in lux, it should be remembered that the human spectral sensitivity data (Chapter 3) used to derive these units applies only to light conditions similar to those used in that experiment. The lux unit uses the CIE standard human spectral sensitivity curve (1983), which was intended to represent the relative spectral sensitivity of a wider age range of humans under a different set of standardised conditions (CIE, 1983; Bartleson, 1984). This is discussed further in section 4.5.2.

Table 4.6 The illuminances perceived by domestic ducks, turkeys and humans when various light sources are isoluminant at 100 lux. The ratios shown of the perceived illuminance for a 60W incandescent (GEC) lamp to that perceived for other light sources are the correction factors the light sources need to be adjusted by to be perceived as iso-luminant to a 60W incandescent (GEC) lamp by the duck, turkey or human.

Light Source	**Illuminance (lux)**	**Perceived illuminance**			**Ratio of duck perceived illuminance for a 60W incandescent (GEC) to other light sources**	**Ratio of turkey perceived illuminance for a 60W incandescent (GEC) to other light sources**	**Ratio of human perceived illuminance for a 60W incandescent (GEC) to other light sources**
		Domestic duck	**Domestic turkey**	**Human**			
60W incandescent lamp (GEC, Pearl)	100	183	180	122			
100W incandescent lamp (GEC, Pearl)	100	183	181	123	1.00	1.00	0.99
25W incandescent lamp (GEC, Pearl)	100	183	180	121	1.00	1.00	1.00
60W incandescent lamp (Marathon)	100	183	180	121	1.00	1.00	1.00
11W Compact Fluorescent lamp (Phillips)	100	170	165	119	1.08	1.09	1.02
40W Fluorescent tube (GEC)	100	157	152	116	1.17	1.19	1.05
11W Fluorescent tube (Phillips)	100	153	148	114	1.20	1.22	1.07
20W Fluorescent tube (Osram)	100	165	161	123	1.11	1.12	0.99
Daylight – at 13:00 BST in August under sunny (some cloud) sky conditions	100	187	187	136	0.98	0.96	0.90

4.4.3 Summary of results

The results of the survey show that the quantity and quality of light in duckling and turkey housing is quite different to the properties of daylight, in terms of source, colour, photoperiod and illuminance. The range of light sources and illuminances in duckling housing was more variable than those employed in turkey housing. Further, the calculation of perceived illuminances for ducks and turkeys suggests that the lux unit, which is often used to measure illuminance, is an inappropriate measure for describing the illuminance perceived for these species.

4.5 Discussion

The overall aims of these investigations were to undertake a survey to characterise the typical light environments used in commercial duck and turkey housing. Previous studies and reviews of the lighting practices used were often incomplete in their description of the lighting environments employed for turkeys, and literature concerning lighting for ducks is scarce. A further aim was to determine the perceived illuminance for ducks and turkeys for these light environments. This was undertaken as the results of Chapter 3 showed that the spectral sensitivity of these birds is different to that determined for humans in the same experiment, and by the methods used to calculate the CIE standard human spectral sensitivity curve (1983). As this latter curve is used to calibrate light meters giving illuminance measurements in the lux unit, this has implications for how illuminance is measured and perceived for species with different spectral sensitivities to that shown by the CIE curve (see Chapter 3).

4.5.1 Characteristics of the light environment in duckling and turkey poult houses

The illuminances measured in commercial duckling and turkey poult houses were much lower than the levels shown for natural daylight in Appendix IV. The illuminances measured are similar to those found by Prescott and Wathes (1999b) in layer and broiler fowl houses, which showed very low illuminances (approximately 3 lux) to be used for broiler fowl and approximately 20 lux for laying hens. The illuminances measured in this study showed turkey housing to be maintained at a generally lower and more uniform range of illuminances than in the duckling houses surveyed. Possible reasons for this could be due to the greater emphasis turkey producers are required to put on this

aspect of management. In turkey production, low illuminances are often employed to control or prevent injurious pecking (FAWC, 1995; Moinard, 2001). This is not so apparent for growing ducklings, for which a wider range of illuminances appears to satisfy production and management requirements. For ducks, feather pecking and abrasion do occur (Wilson, 2000, personal communication), but these are not considered as important a welfare issue as for turkeys and fowl due to their less frequent occurrence. Low illuminances have also been implicated in the aetiology of some other significant poultry welfare problems (see Chapter 2). For example, lameness in turkeys is attributed to the lower levels of activity observed in birds when reared under dim light conditions (Hester et al, 1987). Changes in the morphology of turkeys' eyes have also been found for turkeys reared in illuminances of 2 and 5 lux (Thompson and Forbes, 1999; Thompson, 2001). Many of the turkey houses surveyed used illuminances within this range. These abnormalities when they occur would most certainly have implications for welfare through their effects on behaviour and reduced visual ability in affected birds (see Chapter 2, sections 2.2.2.1 and 2.3.3.2).

Additionally, the spectral power distributions of the artificial light sources measured were of a different quality to daylight (Figure 4.1), and to those published for environments such as under forest and woodland canopies (Endler, 1993; Chiao et al, 2000) and direct daylight (Conduit and Grum, 1964). The environments in which the progenitor species of domestic ducklings and turkeys evolved, would include a range of illuminances from areas of direct sunlight to patches shaded by vegetation, and the ambient light would also include UV_A wavelengths. Of the artificial light sources measured, only the 11W compact fluorescent emitted a significant UV_A contribution (Figure 4.1). Most types of artificial lighting contains little UV_A wavelengths ($315 < \lambda < 380$ nm), which can be perceived by turkeys, and to a lesser degree, ducks (Chapter 3). Moinard and Sherwin (1999) have shown that turkeys prefer UV-enriched lights, and markings in the plumage of these birds are visible under UV_A light (Sherwin and Devereux, 1999). Broiler breeder hens also prefer inspecting cockerels illuminated with UV_A–enriched light (Jones et al, 2001). Such studies suggest that commercial light environments lacking UV_A may limit and/or deny birds the use of visual cues, which may be important for the performance of a range of visually mediated behaviours. However, the use of this type of lighting for poultry is currently under debate, and further investigations are required.

A comparison of the results of the survey can be made with published guidelines and recommendations on the provision of lighting for ducks and turkeys (see Chapter 2, Table 2.3). The RSPCA Freedom Food welfare standards (RSPCA, 1999a; 1999b) recommend a minimum mean illuminance of 20 lux for ducks and turkeys with the provision of at least 6 h continuous darkness. This minimum illuminance was incorporated into the standards in order to stimulate the natural behaviour and activity of the birds and to allow adequate inspection by the stockperson (Le Sueur, 2001, personal communication). The RSPCA considered that the beak trimming of turkeys, provided that it is performed correctly, is more acceptable than maintaining birds under lower illuminances throughout rearing. Of the surveyed duckling houses, 36.8% would have satisfied this criterion for illuminance, but only 6.3% of the turkey poult houses. With regard to photoperiod, only 21.1% of duckling houses complied with this recommendation, compared with the majority (75%) of the turkey poult houses. The 25% of houses which provided less than 6 h darkness did so only for female poults, whilst providing 8 h darkness for males. However, FAWC (1995) recommends a lower minimum illuminance of 5 lux for turkeys and 8 h of uninterrupted darkness, but state that illuminance should be as bright as practicable and reduced only in the event of aggression. Of the turkey poult houses, 35.3% were maintained at this level of illuminance, and indeed at least one producer used this recommendation as company policy. The majority (75%) also complied with the recommendation for photoperiod. The Council of Europe (2001) recommends that turkeys are kept at a minimum of 10 lux, although this survey indicates that most producers are unlikely to use such an illuminance.

The estimates of illuminances given by farm mangers/personnel may have been based on what farm managers/personnel thought the illuminance should have been rather than their perception, i.e. they may have been told that the illuminance should be 5 lux, for example. In most duck (78.9%) and turkey houses (75%) light meters had been used, even if infrequently. The difference between the measured illuminance and the farm managers' estimate may be due to differences in the methods used for measuring illuminance. For example, differences in the location and number of measurements and orientation of the sensor head. This reflects the lack of standardisation in quantifying the illuminance of poultry housing, which is a concern as several welfare codes and recommendations state specific minimum illuminances for ducks and turkeys (see Chapter 2, Table 2.3).

It should be noted that whilst this survey only sampled a relatively small number of duck (19) and turkey (16) houses, the producers who participated are roughly estimated to produce 70% of all duck and turkey meat in the UK (based on estimated figures provided by the producers surveyed, compared to DEFRA statistics; DEFRA, 2003). If the houses surveyed are typical of other housing within these companies then the survey may well reflect a significant proportion of housing for these species in the UK. However, a wider range of housing types are likely to be found that are used by smaller scale producers, in which these different lighting practices and conditions may occur. A limitation of the scope of this survey is that only housing for birds between 1 and 49 days was surveyed. Whilst the production cycle for most growing ducks would be completed within this age range, the survey does not necessarily reflect the lighting practices and environments for turkeys which are reared beyond this age.

4.5.2 The calculation of perceived illuminance for ducks and turkeys

These results indicate that the lux unit, which is used to measure illuminance, is not an appropriate unit for describing the illuminance perceived by a duck or turkey in poultry housing. This agrees with the conclusions of Nuboer et al (1992) and Prescott and Wathes (1999a) for fowl, which have a similar spectral sensitivity to ducks and turkeys (Chapter 3, section 3.5.1). Prescott and Wathes (1999a; 2000) also found that domestic fowl perceive the illuminance from an incandescent light source as greater than that perceived from a fluorescent tube lit to the same lux unit. This is to be expected given the similarity in their spectral sensitivities (see Chapter 3), and the light sources measured (Prescott and Wathes, 1999b).

Table 4.5 gives examples of alternative relative lux units for the illuminances perceived by ducks and turkeys within the housing surveyed for various light sources. However, it was not possible using these data to provide estimations for the perceived illuminance of all houses surveyed. This was because the illuminance measured in some housing for ducks (Table 4.3) was the result of the combined output of a mixture of different light sources. The perceived illuminances were only calculated for single light sources, and so cannot be applied to the illuminance measurements in houses with mixed lighting. This raises the question of how to calculate the perceived illuminance of light environments with more than one source of lighting.

This study derives similar values for the illuminance perceived by both ducks and turkeys, despite the subtle difference found in their spectral sensitivity (Chapter 3). The results of that experiment showed turkeys to be more sensitive to UV_A ($315 < \lambda < 380$ nm) wavelengths, than ducks and to have a lower sensitivity to orange wavelengths ($600 < \lambda < 630$ nm). The reason for this may be that the light sources for which perceived illuminances were calculated in this study did not contain high proportions of UV_A, but did contain much higher proportions of orange wavelengths (see Figure 4.1). Had the illuminance perceived by these birds for a UV_A rich light source, such as a fluorescent black light / blue lamp, been calculated, then a larger difference in the units derived for these species may have been noted. This is only suggested as such calculations have not been made.

The calculations of the perceived illuminance for humans in these investigations are presented for comparative purposes. These units have little practical use as they are only appropriate for the lighting conditions under which humans were tested in the spectral sensitivity experiment (Chapter 3, section 3.3.5.3). In contrast, the lux unit is a standardised unit for the measurement of human perceived illuminance, with reference to the CIE standard human spectral sensitivity curve (1983). This curve is based upon extensive data from over 200 people, ranging in age from 18 to 60 years, of both sexes, tested under standardised conditions (CIE, 1983). Although it is noted in the literature that this standard human curve does not represent human spectral sensitivity under all light conditions (Bartleson, 1984), it continues to be used as the standard for measuring illuminance, fulfilling the practical requirement of standardising illuminance measurement for humans. Whilst it is now feasible to calculate perceived illuminances for ducks and turkeys using the human spectral sensitivity data from Chapter 3, instead of the CIE standard human spectral sensitivity curve (1983), this would provide results in units that are not related to the lux unit, and require measurement in different units. Due to this limitation, and the small sample size used to collect the human spectral sensitivity data, such calculations were not made.

The method (see Appendix V) used to calculate the perceived illuminances for ducks and turkeys in this study are based on a number of assumptions. Firstly, by converting the spectral power distribution of the light sources from radiant power ($\mu W\ cm^{-2}\ nm^{-1}$) into a photon flux, and then into a standardised spectral power distribution, this method assumes that "brightness" perception is based upon the sum of the individual cone

photoreceptor response, as determined by the number of photons per unit of time and not the radiant power of the light source. The latter is traditionally used to calculate perceived luminous flux (or lux) and requires the spectral power distribution of the light source to be expressed in terms of energy units (usually Watts). However, the method used in this study for deriving perceived illuminances does result in units that are technically equivalent to those as expressed in terms of energy. Therefore, the units derived are able to be referred to as units of perceived "brightness" or illuminance, but still consider in their calculation that it is the number of photons that determine the photoreceptor responses which lead to "brightness" perception. Secondly, by converting any perceived illuminances into equivalent lux units to allow practical measurement, it is assumed that the maximum spectral luminous efficacy of radiation for photopic vision in humans (683 lumens/W), as used in the lux unit calculation, is similar to that for the duck and turkey. As no avian data are available, this assumption is made for practical purposes. However, if future research is shown to dispute this assumption then the absolute values given in Tables 4.5 and 4.6 will be incorrect, but the relative values for the perceived illuminances calculated will still be valid.

The perception of the illuminance of a light source is often referred to as "brightness" by humans. This is a psychological response to the intensity of a visual stimulus (Hodos, 1993), and relates to the sensitivity of the luminance channel in the human visual system (Kelber et al, 2003) (see Appendix II, Figure II.1). For example, to humans a light of high illuminance at 700 nm may look as bright as a light of low illuminance at 550 nm. Therefore, as brightness is a subjective visual response, it is not known if animals perceive it as a separate quality to the hue and saturation of light, like humans (Kelber et al, 2003). Additionally, ducks and turkeys both possess retinas which contain double cones, which are not found in the human eye. Osorio et al (1999) has suggested that these may have a function in luminance perception, although this has not been proved experimentally. Therefore, birds may have different visual process to humans for the perception of brightness, and care must be taken that the illuminance of a light source is not referred to as "brighter" for poultry than for a human. The calculations in this chapter do not give any evidence that the birds perceive a light source as brighter than another, only that they require some light sources to be lit to a higher illuminance as measured in lux to be perceived as equal to others (i.e. as if they had the same total power output over the same range of wavelengths).

It should also be remembered that there are some limitations of illuminance measurements for describing how objects in a light environment are perceived. How well an item is perceived is dependent on the amount of light that is reflected from it. This refers to luminance rather than illuminance. However, measurements of luminance are rarely made to describe light environments, and illuminance measurement is easier and more widespread, thus it has been used here for practical purposes. A further limitation of illuminance measurements is that two light sources can be iso-luminant, but not necessarily of equal use to an animal. For example, if a light source lacks a range of particular wavelengths that may be important for mediating certain visual cues, it may still deny the animal use of those cues, despite being of equal illuminance to another light source containing those wavelengths.

4.5.3 Conclusions on describing and measuring the light environment for ducks and turkeys

The findings of these investigations show that both ducks and turkey poults are reared in housing with light environments that differ considerably to those found in the natural habitats of their progenitors. As vision in these birds presumably evolved to function optimally in the range of light environments that prevailed in these habitats, the low illuminances and different colour balances found in commercial houses may affect the visual abilities and performance of certain behaviours for these species (see Chapter 2).

The differences between the farm managers/personnel estimates of illuminance in the duck and turkey houses and that measured highlights the need for a standardised method and guidelines for quantifying illuminance in poultry housing. This could benefit the welfare of ducks and turkeys, through improved monitoring and assessment of illuminance.

The results of these investigations imply that the lux unit is not an appropriate unit for describing illuminance as perceived by ducks and turkeys. This has implications for the provision of artificial lighting in poultry housing. Equating illuminance to the same lux unit in houses which contain different light sources will result in the houses being lit at different illuminances as perceived by ducks and turkeys. Therefore, welfare codes and recommendations that state a minimum illuminance level for these birds will need to account for this, as without specifying light sources type, the illuminance perceived by

the birds could vary by up to approximately 20% based on the findings of this study (Table 4.6). A further implication of these results is that research into the effects of different light sources and wavelengths on ducks and turkeys needs to consider how these species perceive the different light treatments in their experiments if they are not to confound illuminance and wavelength. It is now possible to equate light environments and treatments for ducks and turkeys so that this interaction does not occur.

Chapter 5:

The Preferences of Ducklings and Turkey Poults for Different Incandescent Illuminances

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5.1 Introduction

The poultry industry has been much criticised on welfare grounds for its current practice of housing birds under low illuminances. Research has associated low illuminances with a range of significant poultry welfare issues (see Chapter 2), such as lameness (Hester et al, 1987), eye abnormalities (Ashton et al, 1973; Siopes, 1983; 1984; Thompson and Forbes, 1999; Thompson, 2001) and increased fearfulness (Hughes and Black, 1974), which may perhaps result in the inhibition of foraging and exploratory behaviours (FAWC, 1995). However, increasing illuminance to satisfy these welfare requirements may increase the incidence of injurious pecking in flocks, thus raising the cost of production (Appleby et al, 1992).

To address these issues, a number of welfare, legislative and retailer organisations have published guidelines and recommendations on the provision of lighting for various poultry species. Included in some of these welfare codes for ducks and turkeys are recommendations for minimum mean illuminances for housing (see Chapter 2, Table 2.3). Whilst the need to optimise the light environment in poultry housing is clear, many producers are also concerned that the recommended increases in illuminance will result in increases of injurious pecking among birds, particularly turkeys. Therefore, more scientific information is required on which to base future recommendations. This is acknowledged by organisations like the RSPCA (1999a; 1999b) and FAWC (1995), whilst other reviews (Manser, 1996; Prescott et al, 2003) have also highlighted areas that require further research. These research recommendations include determining the preferences of poultry for illuminance and the levels required for different activities (Manser, 1996).

Preferences for different aspects of lighting such as light source, wavelength and illuminance have been shown by a number of researchers in domestic fowl (Savory and Duncan 1982/83; Appleby et al 1984; Alsam and Wathes 1991; Widowski et al 1992; Berk, 1995; Widowski and Duncan, 1996; Praytino et al, 1997a; Davis et al, 1999;

Vanderberg and Widowski, 2000; Kristensen et al, 2003). The findings of some of these studies are reviewed in Chapter 2, section 2.3.4, and a summary of potentially significant experimental findings relating to lighting parameters for poultry species is provided by Prescott et al (2003). Experiments conducted with turkeys have also found these birds to have preferences for various aspects of light environments. Turkeys prefer compact fluorescent over incandescent lighting (Sherwin, 1999) and fluorescent lighting with supplementary UV_A is preferred to fluorescent light without UV_A (Moinard and Sherwin, 1999). In addition, the preferences of turkeys for different illuminances have also been assessed.

Millam (1987) provided turkey hens with nest boxes of different levels of interior illumination, either high (650-1000 lux), medium (50-150 lux) or low (0.5 lux). The turkey hens preferred nest boxes illuminated with the lowest illuminance regardless of whether they were naïve birds or had had previous experience of using low illuminance nest boxes. However, such preferences pertain only to turkey breeders. Sherwin (1998) gave male turkeys, reared in either 4 lux or 12 lux, a choice of compartments lit by <1, 5, 10 or 25 lux between 6 and 19 weeks of age. Birds reared in 4 lux spent significantly more time in the 5 lux compartment, whilst those reared in 12 lux preferred to spend most time in 25 lux. All birds spent the least time in the dimmest environment (<1 lux). It was suggested by Sherwin (1998) that an illuminance of less than 1 lux might have been aversive to the turkeys. Thompson (2001), using a Y-maze technique, also found that turkeys preferred the brightest illuminance when offered a choice between pairs of intensities selected from 1, 5, 10, 15 and 100 lux. When aged 6 weeks or above, the birds' preference for illuminance was not influenced by rearing intensity, suggesting the existence of innate preferences for illuminance in turkeys (Thompson, 2001; Forbes and Thompson, 2002).

Thompson (2001) also found that the preference of turkeys for illuminance was dependent on age, with birds selecting the higher illuminance less often as the birds aged. However, although this study did investigate the behaviour of the turkeys under each experimental illuminance treatment, this was only completed at 14 weeks of age after the preferences had been assessed. Therefore, this experiment was unable to determine any behaviours that may have been associated with the birds' apparent change in preference with age. In contrast, a study by Davis et al (1999) was able to assess this in layer and broiler strains of domestic fowl. This latter study found that fowl

preferred to perform a number of active behaviours including locomotion and litter-directed pecking in 200 lux compared to 6, 20 and 60 lux at 2 weeks of age. However, the initial preference for bright light weakens as the birds' age, and they begin to prefer to rest and perch in dim light (6 lux) by 6 weeks of age. This suggests that fowl have a preference to perform specific behaviours in different illuminances.

Unfortunately, there is a lack of studies detailing the lighting preferences of domestic Pekin ducks. In general, information concerning the effects of light on this species' productivity, behaviour, health and welfare is scarce. As a consequence, extrapolation from research on other poultry species is often applied, though this may be inappropriate given the different ecology of fowl, ducks and turkeys, and subtle differences in their visual systems. For example, studies into the structure of the duck eye show that these birds have a rod-based retina (Wells et al, 1975) and that they attain full dark adaptation at low illuminance thresholds (see Chapter 2, sections 2.2.1.8.1*i* and 2.2.2.4). This, combined with their reported nocturnal feeding habits in the wild (McNeil et al, 1992), suggests that ducks may show different preferences for illuminance to other poultry species.

Although preference testing has its limitations, it is regarded as an important tool in animal welfare research (Duncan, 1992), and is one way of establishing the suitability of a specific feature of an animal's environment. In a preference test, an animal is given a choice between certain aspects of its environment. The underlying principle is that animals will generally behave to maximise their welfare (Dawkins, 1990) and will therefore preferentially choose the option which is most likely to satisfy their requirements. Whilst different methods have been used, the simplest preference tests consist of providing an animal with two or more options and observing which is chosen. The cost of choosing a particular environment must be consistent between the options available. There are two main types of preference test; a discrete-choice and a free-choice. The first involves an animal being given a choice between the same options on several different occasions, and the number of occasions which an individual chooses a particular option is recorded. In such tests it is common to use a T- or Y-maze apparatus where the animal chooses between two options at the end of a corridor (e.g. Thompson, 2001). In the second type of preference test, an animal is allowed to continually access all options throughout an experimental session. In this method the animal's preference over a longer period of time may be recorded, either as the total time spent in each

option, as visit frequencies, or as the number of animals choosing a particular option. In these tests it is common for the animal(s) to live in the test apparatus (e.g. Sherwin, 1998; Davis et al, 1999).

The assessment of illuminance preferences for growing ducklings and turkey poults lends itself towards the second, free-choice type of preference test for a number of reasons. Firstly, this type of test readily enables the group testing of social animals such as ducks and turkeys, eliminating stress from testing isolated individuals. Secondly, as the preferences of fowl (Davis et al, 1999) and turkeys (Thompson, 2001) are shown to be dependent on age, then studying the preferences of the birds over time enables this to be assessed. Thirdly, a free-choice test would allow the birds to familiarise themselves with the test apparatus, eliminating possible novelty biases. Finally, by using this method it is possible to record behavioural observations of these birds in the different illuminance treatments over a longer period of time than is usually given in discrete-choice tests. The combination of preference testing with recording behavioural observations can be used as a tool to identify changes in the frequency of particular behaviours within different illuminance environments. Portioning time to a particular behaviour represents a choice by a bird. As birds have only a finite period to perform a range of behaviours, any changes between groups located in environments that are identical, except for one parameter, can be attributed to that different parameter.

5.2 Aims and objectives

The aims of these investigations were to use a free-choice test to determine the preferences, if any, of growing ducklings and turkey poults for a range of illuminances (<1, 6, 20, 200 lux), and whether such preferences are influenced by age (2 *vs* 6 weeks) and behaviour.

5.3 Materials and methods

5.3.1 Subjects

Two batches of 30 female ducklings (60 in total) (Cherry Valley SM2I; Cherry Valley Farms Ltd, Market Rasen, Lincolnshire, UK) and later two batches of 30 female turkey poults (BUT Big 6; British United Turkeys Ltd, Chester, UK) were reared from one day

of age. The first batch of each species was obtained one week before the second batch. Females were chosen (particularly with regard to turkeys) to reduce stocking density within the confines of the facilities available, and to keep this study comparable in this regard to previous work (see Chapter 3; section 3.3.1).

5.3.2 Housing and husbandry

The birds were reared in groups of 30 for the first 14 days, and housed in pens with an area of approximately $5m^2$, wood-shavings litter, a feeder (plastic chick trays, BEC, Stevenage, Hertfordshire, UK) and an automatic drinker (Penta drinkers, Giordano, Poultry Plast). From five days of age, poults were also supplied with two perches (1.8 m long x 0.20 m high). The ducklings were provided with a metal tray $1m^2$, above which was a drinker was suspended. Spilt water from the drinker was caught in this tray and emptied twice daily, to maintain litter quality in the rest of the pen, and also make some water available with which the birds could preen. During rearing, the temperature was reduced from 30°C after the first three days, by 1°C d^{-1} to 19°C at 14 days and then maintained approximately at this temperature until the end of the experiment. At 14 days of age each batch of 30 birds was separated into two flocks of 15 birds (i.e. Batch 1 into Flocks 1 & 2; Batch 2 into Flocks 3 & 4). Both flocks from each batch were then housed in separate pens within the same room (one pen being the original used for housing birds until 14 days of age).

The birds were fed conventional starter crumbs, starter pellets and grower rations appropriate to the species and ages of the birds. Ducklings were fed chick crumbs (W. Jordan & Sons, Biggleswade, UK) for the first 21 days and then waterfowl grower pellets (Fenland Range, Clark & Butcher Ltd, Ely, UK). The turkey poults were fed turkey starter crumbs for the first 14 days, then turkey starter pellets until 28 days of age, and finally turkey grower pellets until the end of the experiment (BOCM Pauls Ltd, Ipswich, UK). Food and water in the home pens was provided *ad libitum* to the birds.

As in the spectral sensitivity study (Chapter 3, section 3.3.2), birds of both species were provided with various types of environmental enrichment devices. In addition to those mentioned in Chapter 3, cabbages were also provided, as in this study birds were not food deprived. The turkey poults also were given suspended Pecka-Blocks™ (Breckland

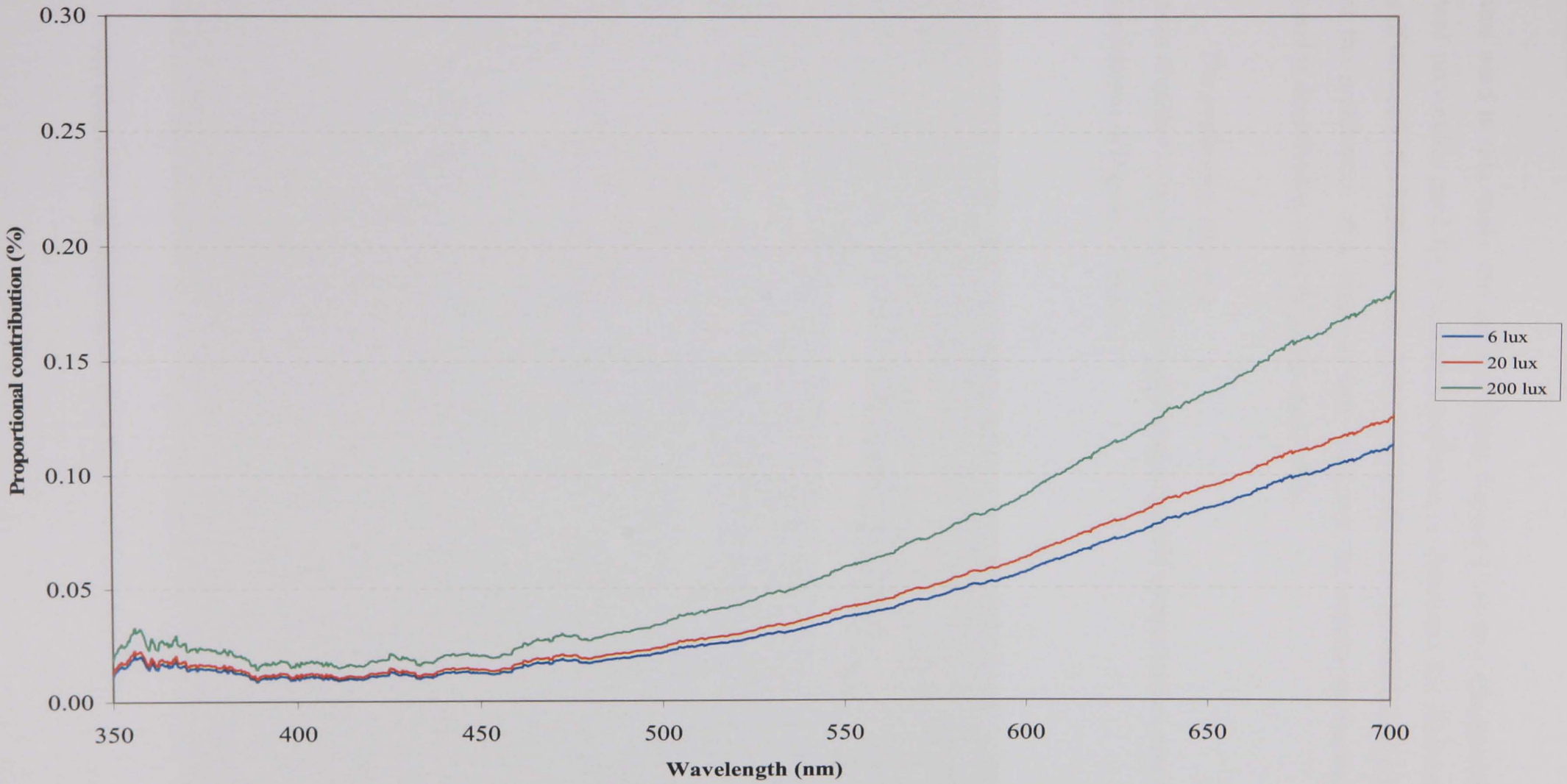
International Ltd, Norfolk, UK). All birds were inspected regularly five times per day throughout the rearing periods.

5.3.3 The light environment in the home pens

The lighting system during rearing was provided by 16 incandescent 60W bulbs (Osram, Pearl) and a series of dimmer switches and timers in each rearing room. From when the birds were 1 day of age, each 24 h period was divided into 6 h blocks of four nominal illuminances, <1, 6, 20 and 200 lux, which were presented according to a randomised schedule. These were the same four illuminances that were later used during the preference tests (see section 5.3.4.2 for the reason these illuminance treatments were chosen). This schedule in the home pens was designed to give the birds' equal experience of the illuminances they would later choose between. The illuminance in the pens was measured by angling the sensor of a calibrated light meter (Macam Photometer, Model L103; Macam Photometrics Ltd, Livingston, UK) in the direction of maximum radiance, as described by Lewis et al (1999) and Prescott and Wathes (1999b). Illuminance measurements were made at a level 20 cm above the litter at 17 points within each pen, and did not vary by more than ± 10 % of the nominal illuminances stated above. This was to ensure the pens were illuminated as evenly as was practically possible. Every week thereafter, the illuminance in the pens was measured in this way, and adjusted when necessary to maintain the illuminances. Adjustments were achieved by use of the dimmer switches.

The photoperiod schedule for the birds was 18L:6D, thus fulfilling welfare recommendations for a minimum period of 6 h darkness (RSPCA, 1999a; 1999b). The dark period was achieved by the provision of the <1 lux period, and due to the randomised schedule, this was usually given at a different point in the 24 h period each day. Measurements of the spectral power distributions of the incandescent luminaires used at each of the four illuminances were made using a spectroradiometer (Model ST2000, Ocean Optics Inc., Dunedin, Florida, USA), and the emissions were found to be similar regardless of the level of dimming. The relative percentage spectral power distributions for the incandescent light source used are displayed in Figure 5.1. Only the three brighter illuminances are shown, as no lamps were switched on to provide the < 1 lux illuminance, and this level of illumination exceeded the sensitivity of the spectroradiometer.

Figure 5.1 The relative percentage spectral power distributions for 60W incandescent (Osram, Pearl) light sources, lit at 6, 20 and 200 lux.



5.3.4 Apparatus

The apparatus used in this study was built at Silsoe Research Institute (Bedfordshire, UK), and was previously used for a similar experiment to determine the illuminance preferences of domestic fowl (Davis et al, 1999). This preference chamber has also been used to test the preferences of a range of farm livestock for various environmental conditions, and is described in detail by Jones et al (1996).

5.3.4.1 The preference chamber

The preference chamber comprised of eight adjoining trapezoid compartments, arranged in an annulus (shown in Figure 5.2 and 5.3).

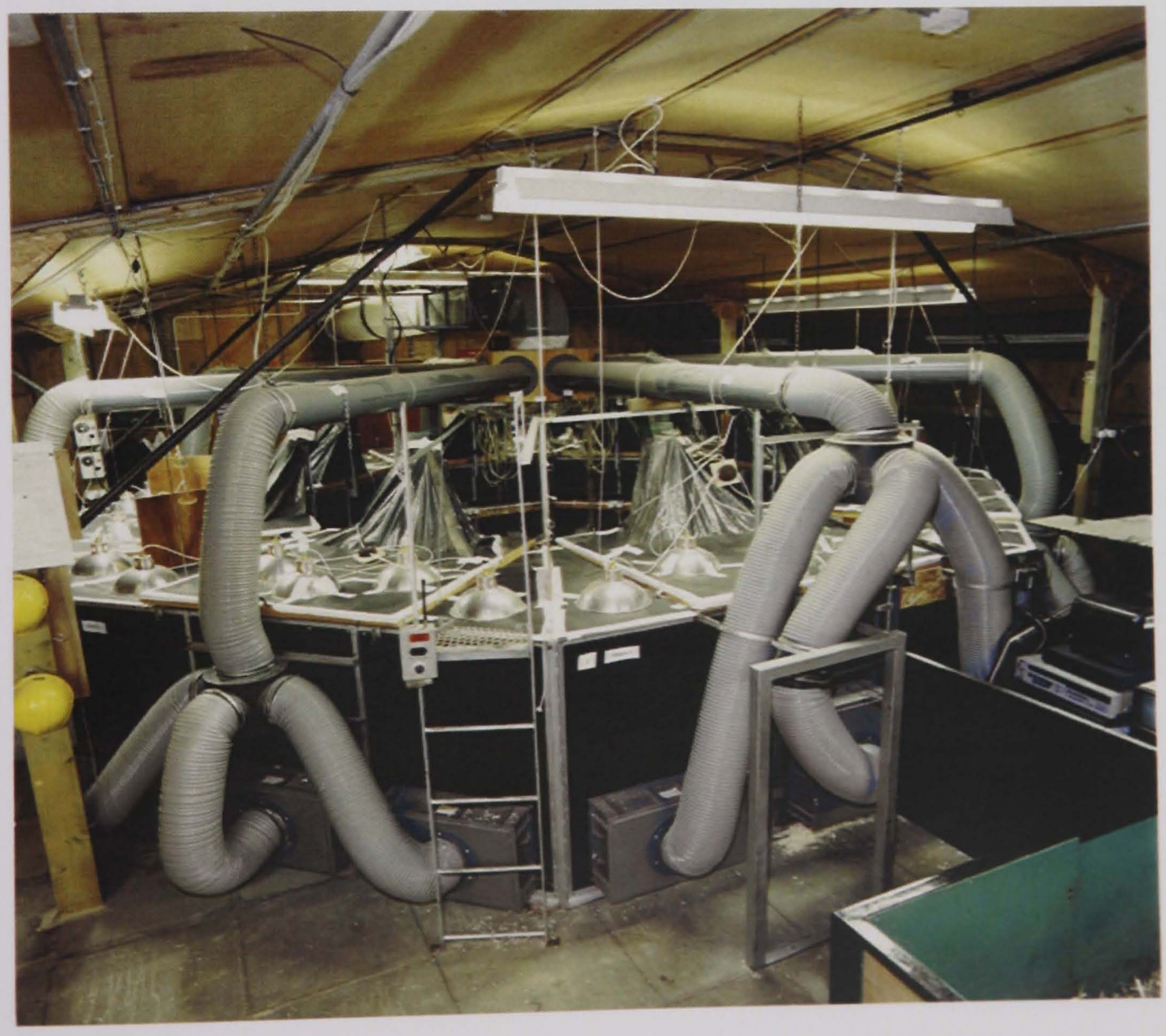


Figure 5.2 An overview of the preference chamber

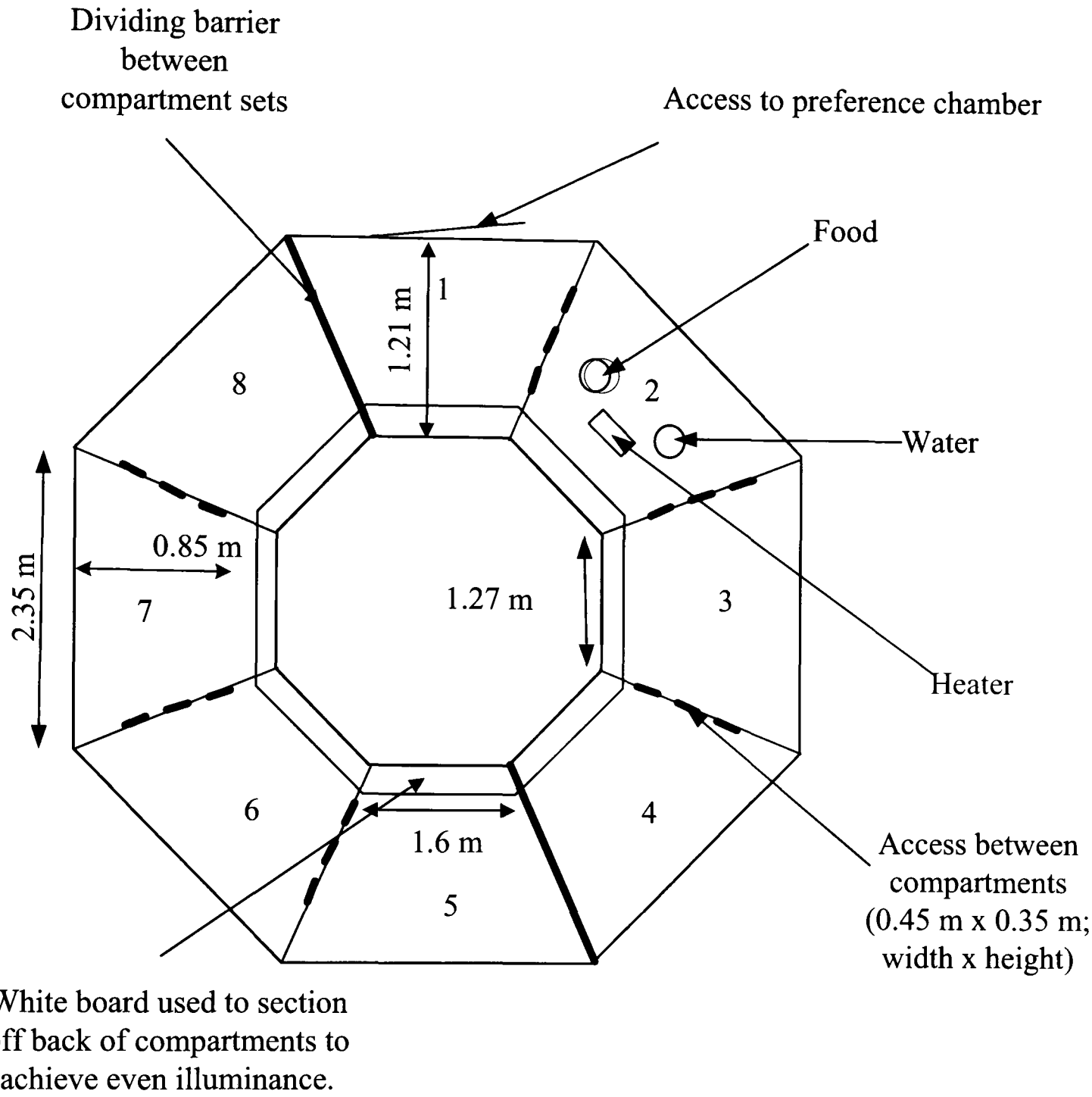


Figure 5.3 A schematic plan view of the preference chamber (not drawn to scale).

The walls and floor of the chamber was constructed of a steel framework with recycled plastic bolted to it (Stokbord™, Braitwaite Plastics Ltd., Worcester, UK). The compartments were identical and measured 1.27 m along the shortest length, 2.35 m along the longest length, 1.21 m wide at the widest point and 1.21 m high. The roof of each compartment consisted of a transparent Perspex sheet on a wooden frame. The central part of this was hinged along its shortest length to allow access for the experimenter. The only other access was via a hinged door in the outside wall of one compartment (see Figure 5.3).

For this experiment, the chamber was divided into two sets of four compartments, allowing two flocks (each from the same batch) to be tested simultaneously. Inside the chamber, compartments were separated by a wall with an opening (0.45 m wide x 0.35 m high) which allowed the birds' easy access to the adjacent compartment, but was low enough to reduce some of the light spillage from the compartments on either side. Each opening could be closed by a guillotine door that was operated from outside the preference chamber. The chamber was ventilated by a two-fan system which drew fresh air from outside the building that housed the chamber. This ventilation system is described by Jones et al (1996). The speed of the fans was set to ventilate the chamber at a rate of 57 air changes h^{-1}. The temperature of the chamber was not closely controlled, but heat was provided by a 750W ceramic radiant heater (producing no light emissions) that was suspended from the roof of each compartment. The maximum and minimum temperatures and humidity were recorded from a thermo-hygrometer (Oregon Scientific) in each compartment.

Each compartment was provided with a feeder (plastic chick trays, BEC, Stevenage, Hertfordshire, UK) containing equal amounts of the appropriate feed, an automatic drinker (Penta drinkers, Giordano, Poultry Plast) and wood shavings litter as in the rearing pens. Compartments for the turkey poults were similarly equipped, but were also provided with perches, strips of plastic feed bags and a Pecka-Block™ to help minimise injurious pecking during testing. The typical compartment layout for the ducklings and turkey poults is shown in Figures 5.4a and 5.4b, respectively.

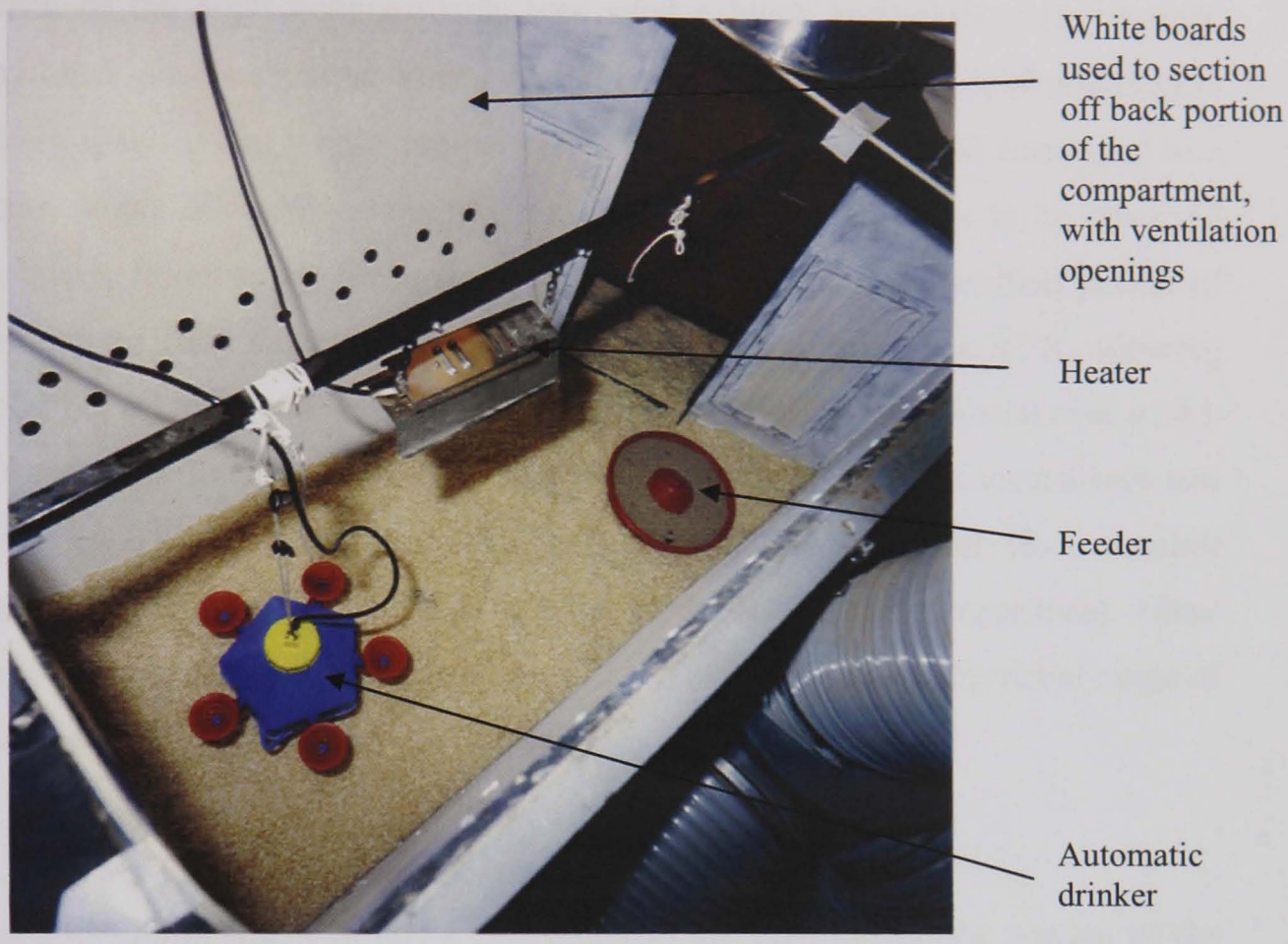


Figure 5.4a The typical compartment layout for ducklings.

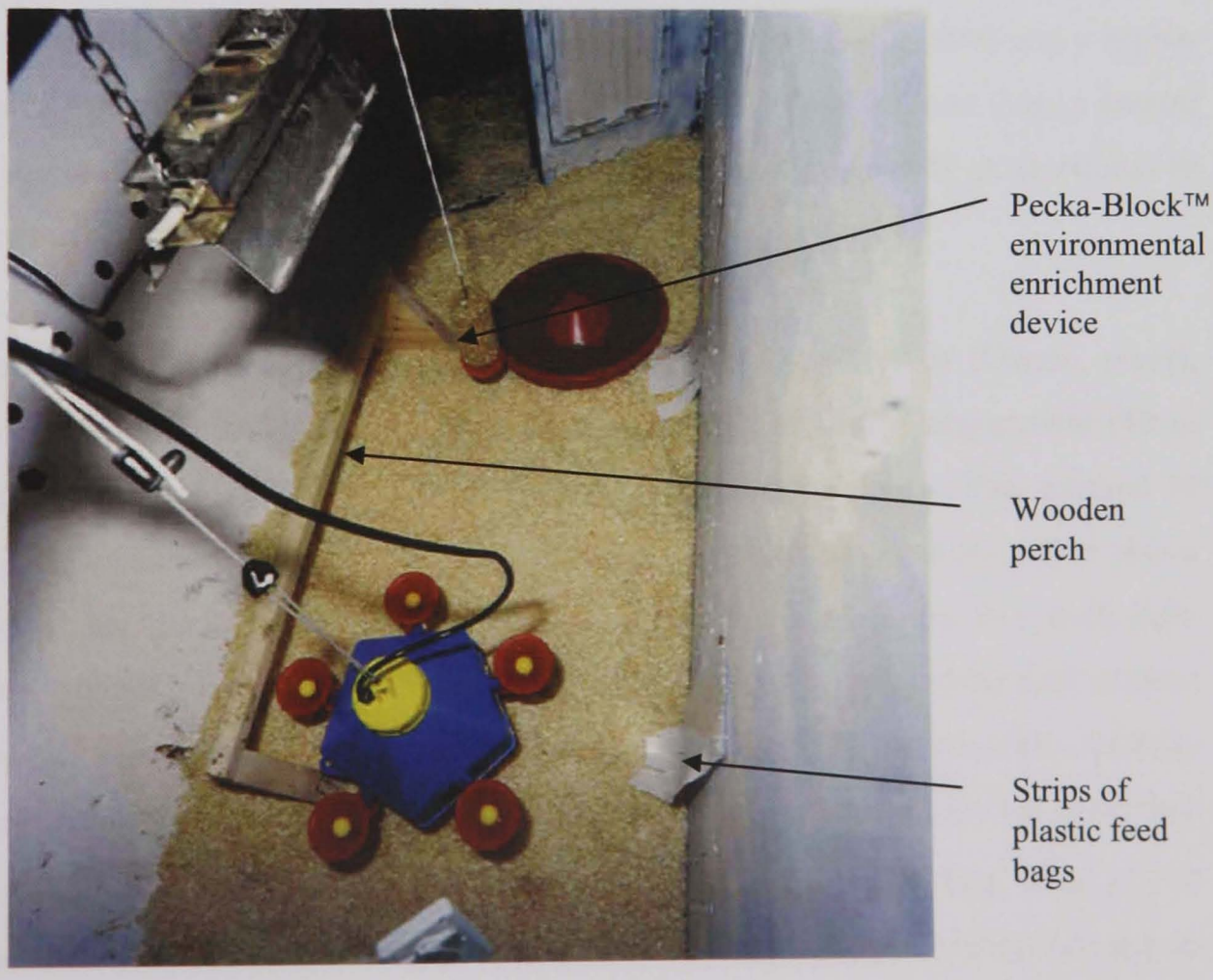


Figure 5.4b The typical compartment layout for turkey poults.

Above each of the eight compartments was sited a black and white video camera, shaded by black plastic sheeting from external light and dust. The view obtained from each camera spanned one whole compartment. These cameras were all connected to a multiplexer, which allowed the output from one set of four cameras to be observed simultaneously, followed by the images of the other four after a specified period of time. The images from the multiplexer were recorded on a time-lapse VCR, allowing the sampling of all eight compartments (alternating between the two halves) over a 24 h period. In order for the images to be recorded when a compartment was set at a very low illuminance (< 1 lux), an infra-red LED illuminator panel (Model IR-2; Anchor Supplies, Ripley, Derbyshire, UK) was attached to the wall of the compartment. These panels emitted radiation with a maximum peak at λ=840 nm; outside the visual range of ducks and turkeys, as determined in Chapter 3.

5.3.4.2 The experimental illuminance treatments

The same four illuminances of <1, 6, 20, and 200 lux used during the rearing of the birds were used in the experiment. These illuminances were chosen to provide the birds with a choice between virtual darkness (<1 lux), an illuminance often used in commercial housing (6 lux), the minimum illuminance recommended by the RSPCA welfare standards for ducks and turkeys (20 lux) (RSPCA 1999a; 1999b) and a higher illuminance for comparative purposes (200 lux). The latter is one log unit ($\log_{10}$) greater than 20 lux, and this was chosen as the growth response is apparently proportional to the logarithm of illuminance (Morris, 1967).

The light environment was provided by five 60W incandescent bulbs (Osram, pearl), placed in reflectors, positioned above the transparent roof of each compartment (40 in total) (as shown in Figure 5.5) and controlled by dimmer switches. This method of dimming the incandescent luminaires to obtain the nominal illuminances stated above was used, rather than neutral density filters for example, as it is the way such light sources are dimmed in commercial practice. Thick black paper covered the roof of each compartment, between the lamps, to exclude extraneous light. The lamps were carefully positioned so that the illuminance within each compartment did not vary by more than ±10 % of the nominal illuminances, as calculated from 16 measurements taken 20 cm above the litter prior to each testing period. The illuminance in each compartment was measured by angling the sensor of a calibrated light meter (Macam Photometer, Model L103; Macam Photometrics Ltd, Livingston, UK) in the direction of maximum

radiance, as used to measure the illuminance in the home pens. In order to achieve as even an illuminance as possible within the chamber compartments, a number of modifications were made. The back portion of each compartment was sectioned off with rigid boards painted white (shown in Figures 5.4a and 5.4b), as illuminances in that part of the compartment fell below ± 10% of the means stated. This reduced the overall floor area of each compartment from approximately 2.4 m^2 to approximately 2.0 m^2 (dimensions are given in Figure 5.2). The internal surfaces of the chamber were also painted white. The spectral power distributions of the light sources set at each illuminance in the chamber were measured, and found to be virtually identical to those measured for the home pens (see Figure 5.1).

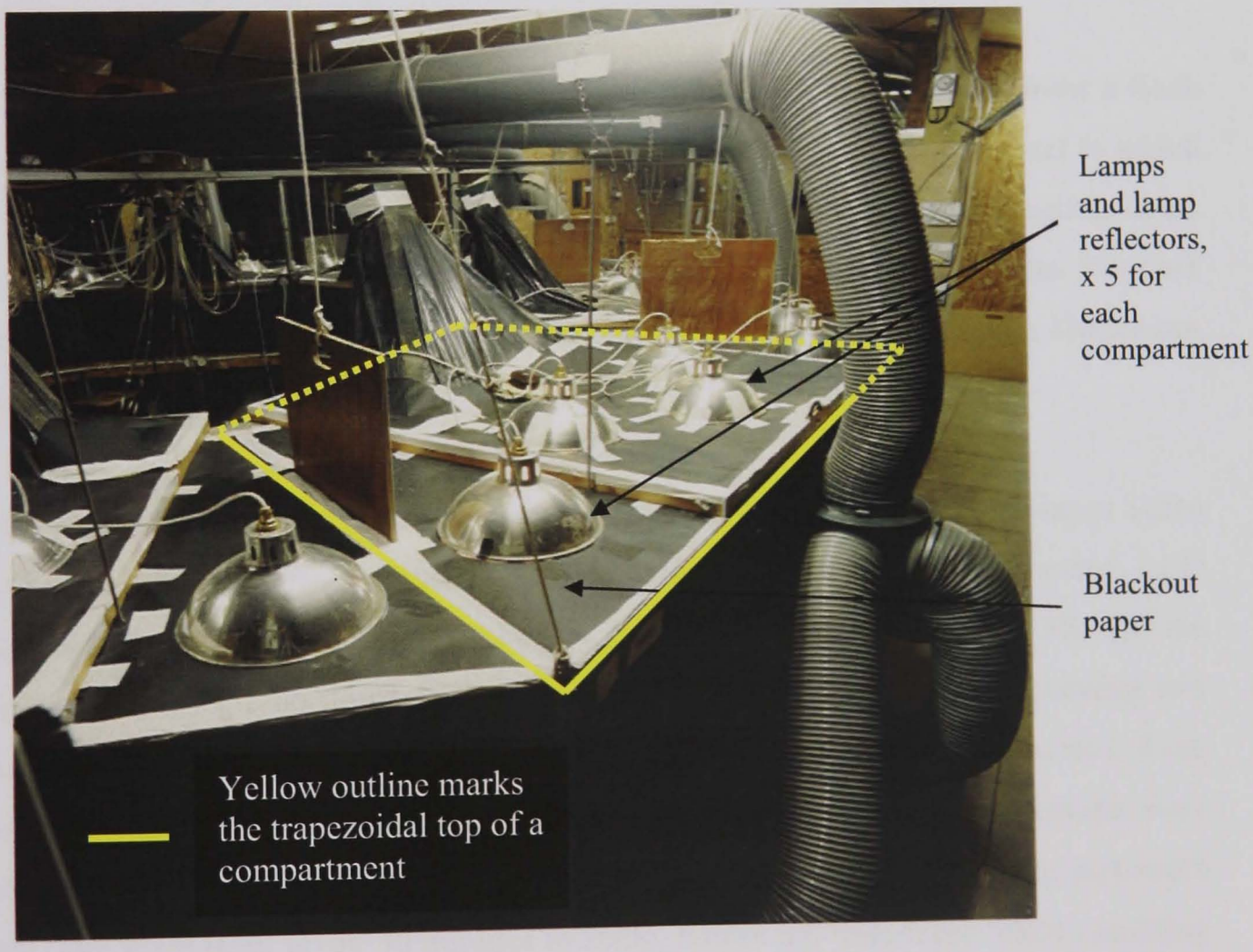


Figure 5.5 View of the preference chamber showing the positioning of the lamps.

5.3.5 Experimental design and protocol

Two flocks from the same batch were tested concurrently; each flock containing 12 birds chosen at random from the 15 reared. Each flock was randomly assigned to each set of four compartments (a compartment set) for six days. The first two days were used to acclimatise the birds to the chamber and the remaining four were the testing period. During conditioning, the four illuminance treatments were presented randomly, but during the testing period the light treatment varied according to a quasi–Latin square design every 24 h. Thus, by the end of the four day testing period each compartment had been illuminated with each illuminance treatment for 24 h. The experimental design for each batch of ducklings and turkey poults, showing the allocation of the illuminance treatments to the compartments is given in Appendix VII, Tables VII.1-VII.4.

At the beginning of the conditioning period (at 10:00-10:30), three birds from a flock were initially placed in each of the four compartments of the compartment set to which they had been assigned to, with all doorways closed. At 10:30 the connecting doors were lifted to allow birds to move freely between the four compartments. No dark period was provided in the preference chamber, since one environment was always un-illuminated (<1 lux).

During testing, the birds' behaviour was recorded over 22 h using time-lapse video recording from cameras positioned above each compartment; the infra-red LED illuminator panel (Model IR-2; Anchor Supplies, Ripley, Derbyshire, UK) allowed the camera to image the inside of the non-illuminated compartment. In the remaining two hours (between 09:00 – 11:00), the feeders were refilled, birds were inspected, fresh wood shavings were added to each compartment and the illuminance treatments were reallocated among the compartments (according to Tables VII.1-VII.4, see Appendix VIII). The birds were given 30 minutes to settle, before the time-lapse video recording was re-started at 11:00. Throughout testing in the chamber, the birds were inspected four times a day, by lifting a corner of the black paper covering the clear Perspex lid of each compartment, and viewing the birds inside. The chamber was not entered to avoid disturbing the birds.

The above procedures were repeated for both species when the birds were two and six weeks of age. Birds that were tested at two weeks of age were identified with coloured

livestock spray marker and the same birds were returned to the chamber at six weeks of age. Between the periods of testing in the preference chamber, the birds were kept in their home pens, and the randomised lighting regime provided previously was continued.

5.3.6 Data recording

Data were collected on each test day between 11:00 and 9:00 the following day. Thus each 'day' covered 22 h. As the videotapes were condensed by a time-lapse VCR to allow recording to take place over each 22 h period, a continuous recording method could not be employed. Instead, data was collected from the videotapes using a time sampling technique. The sampling interval used was determined by the procedure detailed in Appendix VIII. This method indicated that an interval of 10 minutes produced estimates of behavioural time allocation and occupancy of the illuminance treatments that varied within ± 5% of those derived from five-minute interval sampling. Five minutes was used as the minimum scan interval due to the logistics of scanning more frequently from time-lapse video recordings. Thus, an instantaneous scan/ observation (Martin and Bateson, 1993) was made every 10 minutes of each bird, recording both its behaviour and location within a particular compartment. These data were summed over each 22 h period (12 birds x 22 h x 6 observations per hour = 1584 data points d^{-1}) to obtain estimates of the total time spent in each compartment and/or illuminance treatment (occupancy), and the partition of behaviour between the light environments. For the ducklings and turkey poults, nine and 12 behavioural categories were defined and recorded respectively and these are described in Tables 5.1 and 5.2.

Due to a short power-cut during testing at two weeks of age for the ducklings, and the removal of one turkey poult from the chamber, for treatment of minor wounds caused through injurious pecking at six weeks, some data were lost. These were treated as missing values in the statistical analyses. Thus, the mean number of observations d^{-1} (a 22 h period) actually recorded for each species was less than the 1584 total observations d^{-1}, stated above.

Table 5.1 Ethogram used to categorise the behaviour of ducklings

Behaviour	Definition
Standing	bird standing inactive.
Resting	bird sleeping or recumbent.
Stretching	bird stretching a single leg or wing; a wing-and-leg-stretch; or both wings stretched together, vertically.
Preening	preening of feathers with bill, with or without the use of water; using the bill to throw water over the head and body; scratching head with foot; foot pecking and leaning; body, head and wing shaking.
Moving	bird walking or running.
Feeding	head lowered at feeder.
Drinking	head lowered at drinker.
Environment-directed pecking	any floor, wall, litter, door related pecking.
Other	any other behaviours not covered by above categories, or no clear view from the videotapes to determine behaviour.

Table 5.2 Ethogram used to categorise the behaviour of turkey poults

Behaviour	Definition
Standing	bird standing inactive on floor.
Resting	bird sleeping or recumbent.
Perching	bird standing, sleeping or sitting on the perch.
Preening	preening of feathers with beak; scratching head with foot; foot pecking and cleaning; body, head and tail shaking; wing flapping and shaking; dust-bathing.
Preen-perch	above preening behaviours carried out by bird on the perch.
Moving	bird walking or running on ground or perch.
Feeding	head lowered at feeder.
Drinking	head lowered at drinker.
Environment-directed pecking	floor, litter, wall, perch, door related pecking or scratching.
PECKA-BLOCK™ *use*	pecking at PECKA-BLOCKS™.
Feather pecking	pecking at another bird's plumage.
Aggression	birds actively fighting with each other.

5.3.7 Data analysis

The data were tabulated in spreadsheets, in which the total daily counts for overall occupancy and each of the behaviour categories in the four illuminances were summarised. The total of all behaviours performed in one illuminance treatment/compartment was equivalent to the occupancy of that treatment/compartment.

All analyses were carried out using GenStat 5 (Release 4.2, Lawes Agricultural Trust, 1989).

5.3.7.1 Overall occupancy of illuminances

The total time spent in each of the four illuminance treatments (overall occupancy) was analysed using an Analysis of Variance (ANOVA). These data were measured on a ratio scale, and followed a normal distribution, as shown by a histogram of the raw data. The constancy of variances was checked by inspecting the residual versus fitted value plots, and the resulting approximately random scatter shown in plotting this indicated that the variance was constant. Throughout the analysis, the experimental unit was the preference chamber compartment rather than the birds, and the response was the amount of time the birds as a group spent in each illuminance/compartment overall, hence ensuring that the data points were independent. The blocking structure used for this analysis reflects the design of the experiment, and was as follows: age (two and six weeks) was nested within batch (two rearing groups of 30 birds) since each batch of birds was tested at two ages. Compartment set (the two sets of four compartments) was nested within age as each age was tested in each of the two compartment sets. The test days (1-4) and compartment per set (1-4) are crossed as each day each compartment receives one illuminance treatment, and over the four test days, all four. As this interaction occurs within each compartment set it was nested within it. In GenStat notion, the blocking structure was 'batch/age/compartment set/(test days*compartment)'. Having incorporated the random effects into the blocking structure, the treatment structure used identifies the fixed effects to be tested during the experiment. This was all interactions between: age (two and six weeks), flock (the two flocks each containing 12 birds tested concurrently) and illuminance (<1, 6, 20 and 200 lux). In GenStat notion, this was 'age* flock* light'.

5.3.7.2 *Association between illuminance and behaviour*

As the distribution of individual behaviours amongst the four illuminances was not normally distributed, the data were consequently subjected to a logit transformation in order to meet the assumptions of normality to allow analysis using ANOVA. A logit transformation is '$\log_e$ (P/N-P)' where P=the total number of counts recorded each day for the behaviour categories per flock/day, and N =the total number of data points for all behaviour categories per day.

However, in these set of data for the turkey poults many of the combinations of illuminance/compartment treatment and behaviour were not recorded, particularly for the <1 lux illuminance (i.e. the data set contained many zeros). When these logit transformed data were analysed using ANOVA in GenStat, the programme automatically provided an estimate for these "apparently" missing values. However, these estimates were based on the few values that were recorded for these illuminance/compartment treatment combinations, and led GenStat to provide inappropriate estimates. Therefore, on re-analysis, prior to transforming the data, a nominal value of 0.5 was added to every data point so that GenStat was not required to automatically provide an estimate for these values. For the behavioural data regarding the ducklings, the data set contained fewer missing values (or zeros) and thus the estimates provided by GenStat were in keeping with those observed in the raw data. Hence, in the analysis of the behavioural data for ducklings the zeros in the data were treated as missing values.

The transformed data were then analysed using ANOVA (GenStat version 5, Lawes Agricultural Trust, 1989). For the analysis of the behavioural partitioning, an additional blocking factor of 'behaviour' (nine or 12 categories for the ducks or poults, respectively) was nested with the blocking structure previously described. In GenStat notion this was: 'batch/age/compartment set/ (test days* comp)/ behaviour'. This blocking factor was also included in the treatment structure, allowing all interactions between age, flock, light and behaviour to be examined. In GenStat notation this was: 'age* flock* light* behaviour'. The behavioural data were analysed in this way so that the overall change in the 'pattern' of behaviour could be analysed; as a change in the amount of time spent conducting one behaviour will necessarily change the time spent engaged in others. In this analysis, the standard error of the difference of the means is based upon all the behavioural data combined, at the highest level of significant

interaction found, rather than that due to particular behaviours. The transformed means of the behaviour counts that were statistically analysed were back-transformed for presentation purposes.

In the design and analysis of these experiments, the experimental unit is the preference chamber compartment rather than the birds, and the response is the amount of time the birds as a group spend in each compartment overall, and in each compartment conducting particular behaviours.

5.4 Results

Throughout the experiments the 12 birds tested in each flock generally stayed together and behaved as a group.

5.4.1 Overall occupancy of illuminances

5.4.1.1 Ducklings

There was a significant effect of illuminance on the overall occupancy of the compartments by the ducklings (ANOVA, $F_{(3,60)}$=3.18; P=0.030). The birds spent least time in the <1 lux light environment (240 min per bird per day) and most time in the 6, 20 and 200 illuminances (approximately 400 min per bird per day in each). Figure 5.6 shows the combined values of the means generated from the ANOVA for testing at two and six weeks because there was no significant interaction with age (ANOVA, $F_{(3,60)}$=0.55; P=0.652). The ANOVA table for this analysis is presented in Appendix IX, Table IX.1.

5.4.1.2 Turkey poults

The results for the turkey poults showed a highly significant interaction between illuminance and age on the overall occupancy of the compartments (ANOVA, $F_{(3,60)}$=37.8; P= P<0.001). At two weeks of age, the birds spent most of their time in the 200 lux environment (1140 min per bird per day) and least time in the <1 lux environment (approximately 10 min per bird per day). However, at six weeks of age the birds preferred to use the 20 and 200 lux illuminances (479 and 527 min per day per bird, respectively), whilst still spending least time in the <1 lux environment (133 min per bird per day). The means generated from the ANOVA for the interaction between

Figure 5.6. Mean (± SEM) overall occupancy for ducklings at the four different illuminances, taken from the ANOVA analysis (per day = the 22 h observation period rather than 24 h).

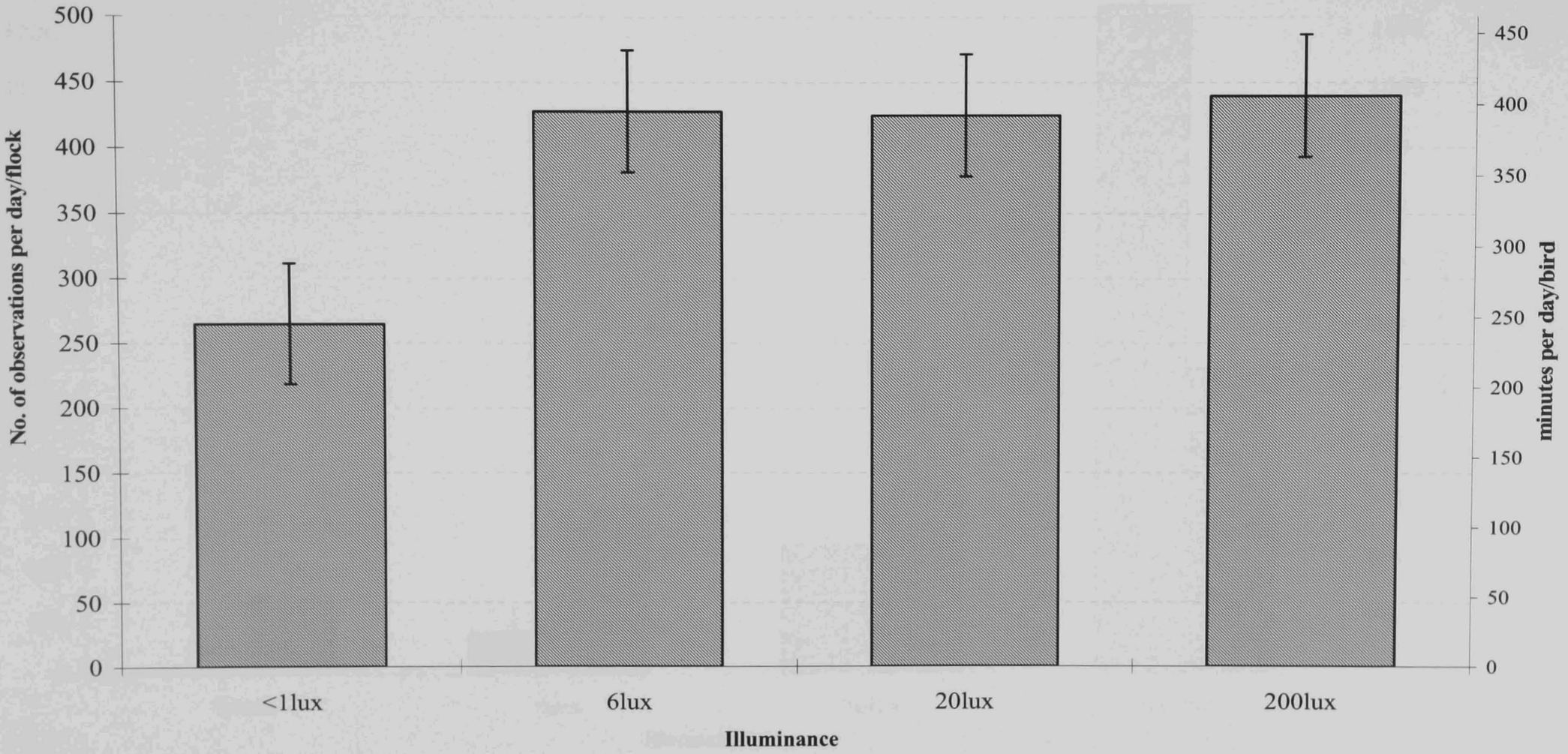
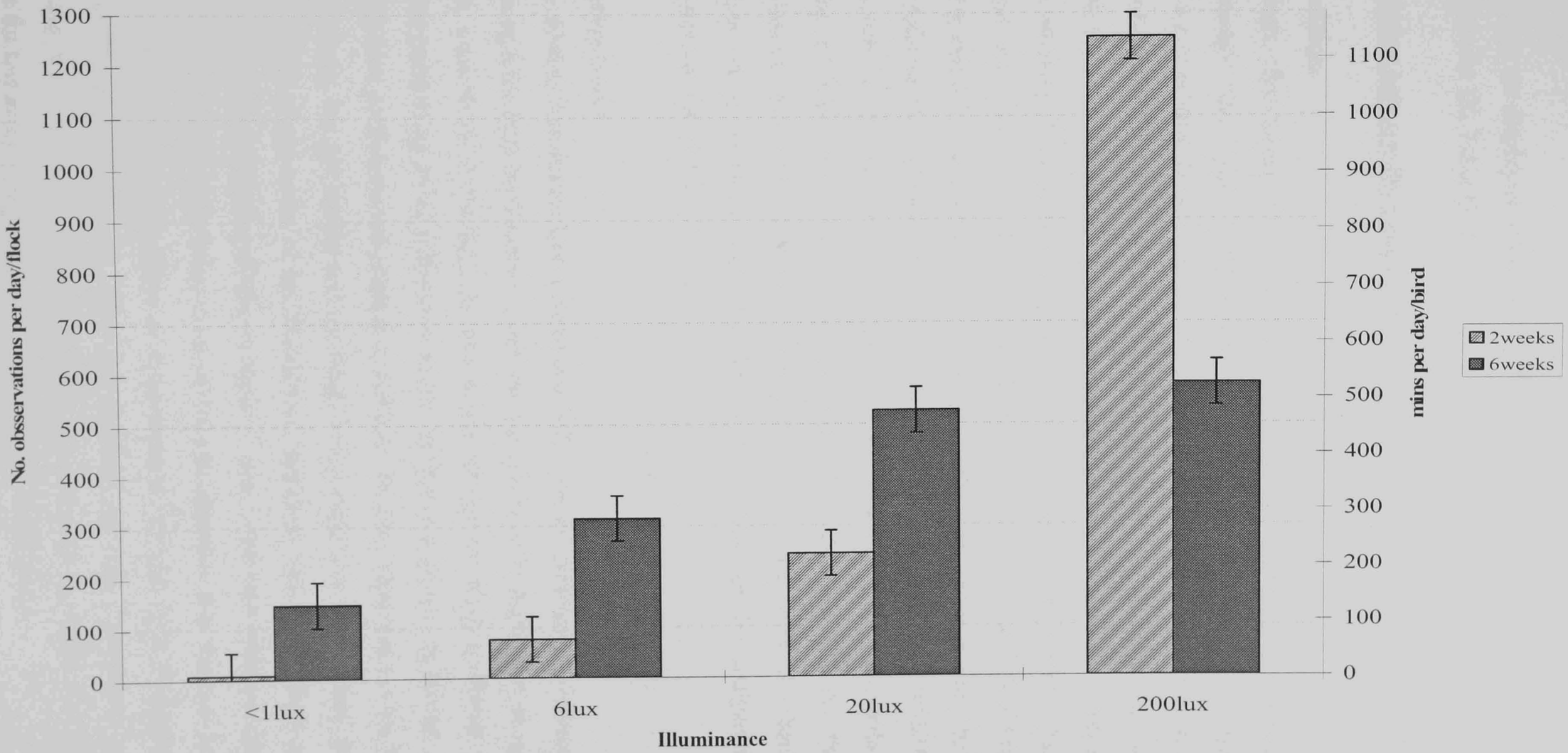


Figure 5.7 Mean (± SEM) overall occupancy for turkey poults at each illuminance, at 2 and 6 weeks of age, taken from the ANOVA analysis (per day = the 22 h observation period rather than 24 h).



illuminance and age are displayed in Figure 5.7. The ANOVA table for this analysis is presented in Appendix IX, Table IX.2.

5.4.2 Association between illuminance and behaviour

5.4.2.1 Ducklings

For the ducklings, illuminance had a significant effect on the partition of different behaviours amongst the light environments, and this was dependent on age ($F_{(24,740)}$=2.74; s.e.d.=0.34; P<0.001). At two weeks of age, the ducklings spent less time moving and performing environment-directed pecking in the <1 lux illuminance, and the most time in the 6, 20 and 200 lux illuminances. However, at six weeks old the birds spent less time preening, feeding, moving, pecking and 'other behaviour' in the <1 lux illuminance and the most in the three higher illuminances of 6, 20 and 200 lux. Standing, resting and drinking at six weeks were also found to occur more in 6 lux than in <1 lux. The total number of observations d^{-1} that could have been recorded was 1584, but due to a power-cut, data were lost (see section 5.3.6). Thus, the mean total number of observations d^{-1} was 1152. The means generated from the ANOVA for the interaction between age and illuminance and behaviour, along with the back transformed data, are presented in Table 5.3. The ANOVA table for this analysis is presented in Appendix IX, Table IX.3.

5.4.2.2 Turkey poults

For the turkey poults, illuminance had a significant effect on the partition of different behaviours amongst the light environments, and this was shown to be dependent on age ($F_{(33,1232)}$=4.50; s.e.d.=0.38; P=<0.001). At two weeks of age the birds preferred to spend most time performing all 12 behaviours in the 200 lux illuminance. However, at six weeks of age their preference had changed to perform 10 of the behaviours in the 20 and 200 illuminances, but not resting and perching. Poults spent less time resting and perching at six weeks of age in the <1 lux illuminance, and most time equally between 6, 20 and 200 lux. The total number of observations d^{-1} that could have been recorded was 1584, but due to a turkey poult being removed from the chamber, data was lost (see section 5.3.6). Thus, the mean total number of observations d^{-1} for was 1536. The means generated from the ANOVA for the interaction between age and illuminance and behaviour, along with the back transformed data, are presented in Table 5.4. The ANOVA table for this analysis is presented in Appendix IX, Table IX.4.

Table 5.3 Mean total daily counts for the behaviours monitored per flock/day, at two and six weeks of age, in the four different light illuminances for ducklings. Data presented are the logit means generated from the ANOVA for the age*illuminance*behaviour interaction ($F_{(24,740)}$=2.74; s.e.d.=0.34; P<0.001), with their respective back-transformed means given in brackets. (Mean total number of daily counts from raw data = 1152; mean total number of daily counts calculated from back-transformed means = 1021.42).

Behavioural Category	**Age of Ducklings**							
	2 weeks				**6 weeks**			
	Illuminances (lux)				**Illuminances (lux)**			
	<1	**6**	**20**	**200**	**<1**	**6**	**20**	**200**
Standing§	-5.37 (7.35)	-4.85 (12.29)	-5.33 (7.62)	-4.94 (11.24)	-4.26 (22.17)	-3.37 (52.43)	-3.94 (30.15)	-3.59 (42.43)
Resting	-2.34 (139.70)	-1.98 (192.88)	-2.27 (148.68)	-1.96 (194.94)	-2.78 (92.75)	-1.82 (221.03)	-2.39 (132.81)	-2.18 (161.44)
Stretching	-5.44 (6.84)	-5.21 (8.63)	-5.32 (7.71)	-5.00 (10.60)	-5.71 (5.21)	-5.31 (7.83)	-5.55 (6.11)	-5.77 (4.94)
Preening†	-4.26 (22.16)	-3.90 (31.41)	-3.89 (31.70)	-3.65 (40.14)	-4.26 (22.17)	-3.41 (50.86)	-3.79 (35.07)	-3.41 (50.79)
Moving*	-5.98 (3.99)	-4.79 (13.01)	-5.26 (8.23)	-4.65 (14.95)	-5.08 (9.77)	-4.10 (25.81)	-4.36 (19.99)	-4.01 (28.28)
Feeding†	-5.55 (6.12)	-4.69 (14.43)	-5.10 (9.63)	-4.99 (10.75)	-5.72 (5.20)	-4.93 (11.34)	-5.03 (10.30)	-4.81 (12.77)
Drinking§	-5.87 (4.46)	-5.29 (7.98)	-5.40 (7.12)	-5.14 (9.25)	-5.80 (4.79)	-4.98 (10.81)	-5.72 (5.17)	-5.13 (9.35)
Environment-directed pecking*	-4.94 (11.29)	-3.98 (29.19)	-4.06 (26.82)	-3.91 (31.10)	-5.06 (10.03)	-3.98 (28.93)	-4.07 (26.52)	-3.82 (34.08)
Other†	-6.86 (1.66)	-6.67 (2.01)	-7.66 (0.75)	-7.35 (1.02)	-8.46 (0.33)	-6.75 (1.85)	-7.15 (1.24)	-7.00 (1.44)

*Superscripts signify behaviours that are performed significantly less in <1 lux than 6, 20 and 200 lux at both ages (P≤0.05). †Superscripts signify behaviours that are performed significantly less in <1 lux to 6, 20 and 200 lux at 6 weeks of age (P≤0.05). § Superscripts signify behaviours that are performed significantly less in <1 lux than 6 lux at 6 weeks of age (P≤0.05).

Table 5.4 Mean total daily counts for the behaviours monitored per flock/day, at two and six weeks of age, in the four different light illuminances for turkey poults. Data presented are the logit means generated from the ANOVA for the age*illuminance*behaviour interaction ($F_{(33,1232)}$=4.50; s.e.d.=0.38; P=<0.001), with their respective back-transformed means given in brackets. (Mean total number of daily counts from raw data = 1536; mean total number of daily counts calculated from back-transformed means = 1265.20).

Behaviour Category	**Age of Turkey Poults**							
	2 weeks				**6 weeks**			
	Light illuminance (lux)				**Light illuminance (lux)**			
	<1	**6**	**20**	**200**	**<1**	**6**	**20**	**200**
Standing*†	-7.16 (1.23)	-6.37 (2.71)	-5.82 (4.67)	-2.72 (97.51)	-6.14 (3.39)	-4.94 (11.27)	-4.22 (22.88)	-3.82 (33.97)
Resting*§	-7.72 (0.70)	-5.89 (4.35)	-5.08 (9.84)	-0.95 (441.31)	-5.45 (6.76)	-2.63 (106.06)	-2.03 (183.65)	-2.01 (187.41)
Perching*§	-8.06 (0.50)	-6.52 (2.33)	-5.46 (6.68)	-2.25 (151.61)	-4.99 (10.68)	-3.14 (65.88)	-2.52 (117.79)	-2.68 (102.09)
Preening*†	-7.76 (0.67)	-6.77 (1.81)	-5.85 (4.56)	-2.64 (105.21)	-6.49 (2.40)	-4.85 (12.25)	-4.02 (27.98)	-3.50 (33.01)
Preen – perch*†	-8.06 (0.50)	-7.38 (0.99)	-6.45 (2.51)	-3.96 (29.55)	-5.88 (4.41)	-5.22 (8.52)	-3.89 (31.64)	-4.07 (26.54)
Moving*†	-7.50 (0.87)	-6.61 (2.13)	-5.79 (4.83)	-3.24 (59.99)	-6.33 (2.82)	-5.60 (5.82)	-4.41 (19.10)	-4.28 (21.62)
Feeding*†	-7.32 (1.05)	-5.96 (4.06)	-5.89 (4.38)	-3.69 (38.55)	-6.73 (1.89)	-5.83 (4.64)	-4.91 (11.57)	-4.52 (17.03)
Drinking*†	-7.99 (0.54)	-7.23 (1.15)	-6.27 (3.00)	-3.38 (52.13)	-7.66 (0.75)	-6.63 (2.09)	-4.92 (11.52)	-4.36 (19.92)

Table 5.4 (Cont.) Mean total daily counts for the behaviours monitored per flock/day, at two and six weeks of age, in the four different light illuminances for turkey poults. Data presented are the logit means generated from the ANOVA for the age*illuminance*behaviour interaction $F_{(33,1232)}$=4.50; s.e.d.=0.38; P=<0.001), with their respective back-transformed means given in brackets. (Mean total number of observations from raw data = 1536; back-transformed mean total number of observations = 1265.02), continued.

Behaviour Category	**Age of Turkey Poults**							
	2 weeks				**6 weeks**			
	Light illuminance (lux)				**Light illuminance (lux)**			
	<1	**6**	**20**	**200**	**<1**	**6**	**20**	**200**
Environment-directed pecking*†	-7.40 (0.97)	-6.12 (3.48)	-5.41 (7.08)	-2.08 (176.60)	-6.52 (2.32)	-4.51 (17.17)	-3.59 (42.47)	-2.99 (75.38)
Pecka-Block™ use*†	-8.06 (0.50)	-8.06 (0.50)	-6.99 (1.45)	-4.76 (13.52)	-7.90 (0.59)	-7.85 (0.62)	-6.67 (2.01)	-5.99 (3.95)
Feather pecking*†	-8.06 (0.50)	-8.06 (0.50)	-7.84 (0.62)	-5.73 (5.11)	-7.91 (0.58)	-7.37 (1.00)	-6.31 (2.87)	-5.77 (4.91)
Aggression*†	-8.06 (0.50)	-8.06 (0.50)	-8.06 (0.50)	-7.25 (1.12)	-7.95 (0.56)	-8.05 (0.50)	-7.54 (0.83)	-6.81 (1.74)

*Superscripts signify behaviours that are performed significantly more in 200 lux than <1, 6, and 20 lux at two weeks of age (P≤0.05). †Superscripts signify behaviours that are performed significantly more in 20 and 200 lux than <1 lux and 6 lux at 6 weeks of age (P≤0.05). § Superscripts signify behaviours that are performed significantly less in <1 lux to 6, 20 and 200 lux at 6 weeks of age (P≤0.05).

5.4.3 *Summary of results*

The results of these experiments show that ducklings and turkey poults have different preferences for illuminance when tested in a free-choice test. Overall, ducklings preferred to spend less time in <1 lux, and this preference was not affected by age. In contrast, turkey poults showed an overall preference for 200 lux at two weeks of age, and for illuminances ≥20 lux at six weeks. For both species, illuminance had a significant effect on the partition of behaviours amongst the illuminances, and for some behaviour categories this was dependent on age.

5.5 Discussion

The results of the light environment survey (see Chapter 4) showed that ducklings and turkey poults are often reared under relatively low illuminances, in comparison to natural daylight or illuminances often used for humans (i.e. offices; see Appendix IV). Recommendations for a mean illuminance of 20 lux for these birds have been published (RSPCA, 1999a; 1999b), with the aim of addressing some of the welfare issues associated with rearing poultry in low illuminances, but producers are concerned that this will increase injurious pecking, particularly in turkeys. The overall aims of these experiments were therefore to identify if ducklings and turkey poults have a preference for illuminance when given a free-choice between levels of <1, 6, 20 and 200 lux, and to see whether such preferences are influenced by age and behaviour.

5.5.1 *Interpretation of duckling and turkey poult preferences for illuminance*

The overall occupancy results in this study indicate that ducklings and turkey poults demonstrate significant, but different, preferences when allowed to choose between a range of illuminances in a free-choice test. As ducklings spent most of their time overall in 6, 20 and 200 lux, these results could indicate either that these birds do not show a clear preference for any particular illuminance above 6 lux, or that the birds chose to access equally all three of these illuminances when provided. This reasoning illustrates the care required when interpreting the results of preference tests (see Dawkins, 1976; Duncan, 1978), and the limitations of the method must be recognised before conclusions can be formed (see section 5.5.3). In addition, illuminance and age were found to have a significant effect on the partition of the different behaviours amongst

the light environments. At two weeks of age, the exploratory behaviours of moving and environmentally-directed pecking occurred most in 6, 20 and 200 lux; whereas at six weeks maintenance behaviours of feeding and preening also occurred more often in these light environments, as well as 'other behaviours'. Except for standing, drinking and resting occurring more in 6 lux than <1 lux at six weeks of age, all other behaviours were not found to be preferentially associated with any specific illuminance.

The turkey poults however, showed a more highly significant overall preference, and an effect of illuminance on the partition of the different behaviours amongst the light environments. These results suggest that two week old turkey poults show a clear preference for 200 lux, but at six weeks of age prefer illuminances of 6 lux or greater for the inactive behaviours of resting and perching, and illuminances of 20 lux of greater for all other activities. This may indicate that at 6 weeks of age turkey poults do not show such a clear preference for an illuminance as at 2 weeks, or that they prefer to access a greater range of illuminances for a number of behaviours, particularly resting and perching when older (six weeks of age). An illuminance of <1 lux was the least preferred choice overall, and for the performance of all behaviours, at both ages.

The occupation of an illuminance of <1 lux by ducklings for 240 min per bird per day, and approximately 10 min per bird per day at two weeks of age and 133 min per bird per day at six weeks for turkey poults indicates this is the least preferred illuminance of those tested (Figures 5.6 and 5.7). This may not necessarily imply that they find it aversive. That these birds choose to spend some time in relative darkness (<1 lux) suggests that it may still be important for them to have access to such illuminance, particularly for ducks and may be also for turkeys at six weeks of age. These results could be interpreted as a crude estimate of preference for photoperiod, although it must be stressed that this interpretation is tentative; previous studies have highlighted the benefits for fowl of longer periods of darkness such as higher feed conversion ratios, fewer leg and eye problems and lower mortality (Classen, 1991; Gordon and Tucker, 1997). This also highlights the concern with preference tests that animals may choose according to short-term benefits, which may conflict with long-term benefits to their welfare (Duncan, 1992).

5.5.2 *Comparison of duckling and turkey poult preferences for illuminance to previous work*

The results of the present study differ to those preferences found for fowl using similar methods (Davis et al, 1999), in which broiler and layer fowl (two weeks old) had a strong preference for a high illuminance (200 lux), and that this preference was influenced by the age of the birds. At six weeks old, their overall preferred illuminance changed to 6 lux, and this change was attributable only to a change in preference for resting and perching in the lower illuminance (6 lux). In contrast, this study shows the overall preferences of ducklings do not change with the age of the birds. For turkey poults their overall preference was also influenced by age, but whilst this was attributable to resting and perching, their change in preference from a high illuminance (200 lux) at two weeks of age was to a non-exclusive preference to perform these behaviours most in 6, 20 and 200 lux. However, the overall occupancy results of the present study do correspond to the findings of Thompson (2001), who also found that turkeys overall preferred the brightest illuminance when offered a choice between pairs of illuminances selected from 1, 5, 10, 15 and 100 lux in a Y-maze test, but that as the birds aged (2 to 14 weeks) they tended to select the higher illuminance less often. The findings of this and the present study highlight the importance of studying the preferences of these birds over time.

Sherwin (1998) also found that turkeys spent the least time occupying <1 lux, when given a free-choice between that illuminance and 5, 10, or 25 lux, presented in a photocline. In that study, turkeys were only observed in the chamber lit at <1 lux when the birds were placed in that chamber at the start of the observations, and were never observed to re-enter it after moving. From these findings, Sherwin (1998) suggested that the birds may possibly find this illuminance aversive. However, it may be that turkeys were encouraged to stay in brighter light because they found it more attractive and visually stimulating. In contrast, the turkey poults in the present study were observed in the <1 lux illuminance, but it was the minority choice at both ages. It is possible that observations of the birds in this illuminance may be due to the birds either moving through the compartment in order to access the other illuminances, or that the birds were monitoring their environment, performing checks to see if the conditions had changed (Nicol, 1997). Ducks and turkeys do not perceive infra-red wavelengths (see

Chapter 3), so the spectral contribution of the infra-red LED panels to aid observation of the birds should not have contributed to their preference.

No previous studies have investigated the illuminance preferences of domestic Pekin ducklings. However, their observed overall preference to spend the least amount of their time in <1 lux is consistent with the general preferences of fowl and turkeys for light rather than darkness for the majority of the time available (Savory and Duncan, 1982/83; Sherwin, 1998).

5.5.3 Benefits and limitations of method

As stated above (5.5.1), a certain amount of care needs to be exercised in the interpretation of preference experiments, as these tests make a number of assumptions. In a preference test, it is assumed that the animal is able to choose the test condition based on how it 'feels' and that the choice made represents the condition which is associated with the best interests of its welfare (Dawkins, 1976; 1990; Duncan, 1992). This study assumed that the ducks and turkey poults were able to move through the chamber compartments freely, and that the birds were able to make the association between any negative or positive state they were experiencing and the light environment they were in, and also associate a change in this subjective state with moving between illuminances. Further, a number of limitations and difficulties in interpreting the results of such tests are identified in the literature, and some of these can result from the experimental set-up. Therefore, the present study was undertaken with consideration of these and the design of the preference chamber and the experimental method was designed to control or eliminate several potentially confounding factors.

Familiar environments are usually preferred to new or novel ones (Dawkins, 1980; 1983). Therefore, to make an informed choice an animal must have experienced the consequences of each alternative (Hughes, 1976; Blom et al, 1993). Previous experience can also influence the results of behavioural tests similar to the present study (Dawkins, 1976; Duncan, 1978). Therefore, the choice of the rearing environment prior to testing was designed to give the birds equal levels of previous exposure to light environments which they were later required to choose between. While this form of light presentation was unrepresentative of commercial practice in respect to the changing illuminance during the day, the illuminance ranges and luminaire types are similar to those used on

some farms, as described in the survey detailed in Chapter 4. Further, it is also important to allow the birds to familiarise themselves with the test apparatus since preferences may otherwise be confounded with exploration of the apparatus itself. Thus, the birds were given two days in the preference chamber for acclimatisation prior to testing at each age.

In preference experiments with socially grouped animals, dominance status can influence the response (Dawkins, 1980), since the preferences shown may be those of the dominant member of the group. In this experiment, detailed social analysis was not possible since the birds were not individually marked, and due to problems of identifying such behaviours on the videotapes, particularly when the birds were young. In the present experiment, the birds of both species predictably behaved as a group, and it is conceivable that a few key birds led the preferences. However, it was viewed that a group of birds was closer to normality than the testing of individuals, which would have had welfare implications through possible stress caused by social isolation.

The experimental design divided the chamber into two sets of four compartments and enabled the preference chamber to be efficiently utilized, as two flocks could be tested at the same time. Alternatively, one flock at a time could have been given access to all eight of the compartments, and two compartments could have been lit with each illuminance treatment. This alternative would have removed any potential compartmental bias resulting from birds choosing a compartment because it was the "end" choice. In the present study, it is possible that birds could have heard the flock in the adjacent set of compartments through the closed guillotine doors and congregated for periods in these compartments for that purpose, although when viewing the videotapes this was not observed to occur often. However, the presentation of the illuminance treatments randomly in the eight compartment configuration could have resulted in adjacent compartments being the same illuminance treatment. Had this occurred, it may have hindered the birds' ability to learn to associate moving compartment with a change in subjective state, as moving would not have necessarily implied a change of light environment. Thus, the experimental design used was chosen as it enabled the preference chamber to be used more efficiently, and its advantages were deemed to out way the disadvantages stated. This also kept the design comparable to that of the Davis et al (1999) study using domestic fowl, making comparisons between the species easier.

The design of the preference chamber enabled the assessment of the birds' preferences over a length of time as the birds were able to be kept in the chamber, and returned for the same period of time at a later age. Thus, the experimental design allowed the assessment of any change in preference to be noted. In addition the observations of the birds' behaviour, including that in the <1 lux illuminance, as well as the location in the light environments, has some advantages over previous studies. Sherwin (1998) was unable to observe the behaviour of turkeys in the <1 lux chamber, whilst Thompson (2001) observed the behaviours associated with illuminance preferences only at 14 weeks of age, after the initial preferences of the birds had been recorded. However, some limitations of the behavioural observation methods used were found. The quality of the video images recorded and choice of the sampling interval hindered the accuracy of recording some behavioural categories because they occurred very infrequently or for short durations, i.e. fighting. It was also necessary to include an 'other behaviour' category in the ethogram for the ducklings. This was mainly used to describe the behaviour of ducklings when they were observed to be under the automatic drinker in a compartment where they were almost totally screened from the view of the camera; which occurred more at six weeks of age because the drinkers had been raised up from the floor in keeping with the growth of the birds. However, other behaviours that could not be categorised from the videotapes are included in this category.

It is noted that a large amount of additional information concerning the behavioural responses of ducklings and turkey poults to these illuminances could have been extracted from the videotape recordings made. For example, the frequency of visits to and their durations in particular light environments potentially could have been determined. This would have allowed more specific evidence of illuminance preferences to have been made from the study, and could have also been used to provide information on the birds' preference to exit rather than enter a specific environment. These investigations would require different sampling methods to extract such data than those used in the present study.

The decision to use incandescent luminaires to provide the illuminance treatments in this study was based on the findings of the survey (Chapter 4), which showed a higher proportion of all the surveyed duckling and turkey houses, combined, had this light source installed (see Tables 4.3 and 4.4). Thus the use of incandescent light sources was

chosen to reflect commercial practice. Whether the results of these preference experiments are applicable to fluorescent or other types of luminaire is unknown, as the results of any preference test are relative, and can only be interpreted within the boundaries of the experimental light conditions tested (Duncan, 1978). As light sources differ markedly in their spectral power output or colour balance (Prescott and Wathes, 1999b; Chapter 4), this may influence any preference. Therefore, there may be interactions between illuminance and wavelength depending on the light source used. As shown in Chapter 4, the illuminance of these light sources will be perceived differently by ducks and turkeys if lit to the same illuminances as used in the light treatments of the present study. Therefore, other luminaire types lit to the same absolute illuminances as those used in this experiment (when measured in lux), may not produce the same effects as observed in the present study for these species.

5.5.4 Illuminance preferences and their relation to the visual abilities and ecology of the duck and turkey

One possible explanation for the different illuminance preferences found in this study between duckling and turkey poults relates to the differing structure of the birds' eyes and/or their ecology. The numbers of cone and rod photoreceptors in the retina of the duck eye are approximately 40% and 60%, respectively (Wells et al, 1975). Mallard, the progenitors of domestic ducks, have also been shown to be able to attain full dark adaptation of the eye at low illuminance thresholds (0.15 lux), suggesting that these birds are adapted for photopic vision in a range of low illuminances including those often found in twilight and full moon conditions (Wells et al, 1975). In comparison, many diurnal birds such as fowl are found to have a higher proportion of cones to rods. The cone-based retina of the domestic fowl contains 60% cones and 40 % rods (Meyer and May, 1973). There are no studies describing the proportions of cone and rod cells for turkeys, but it may be appropriate to assume that they also possess a cone-based retina, given the diurnal nature of these birds. This adaptation indicates that diurnal birds have better vision in brighter light conditions (King-Smith, 1971).

Ducklings in the current study showed a significant preference to perform less feeding behaviour in <l lux at 6 weeks of age. This particular preference is interesting as there is behavioural evidence that these birds do not require visual cues for foraging and can be guided exclusively by tactile cues (Martin and Lett, 1985; cited by Jane, 1986). Why

ducklings should prefer to feed in illuminances of 6 lux or greater at six weeks of age, but not two weeks, like turkeys and fowl (Davis et al, 1999) is unclear. However, the results of this study suggest that whilst there is evidence ducks are not dependent on vision and light for feeding (Martin and Lett, 1985; cited by Jane, 1986; Martin, 1986; McNeil et al, 1992) (see Chapter 2, section 2.2.2), they do show an illuminance preference for this behaviour. That ducks will feed nocturnally in the wild may be due to a number of factors: if daytime feeding is disturbed, to avoid daytime predation or because certain food sources may be more available at this time (McNeil et al, 1992). Without these pressures, birds may change their feeding habits. That turkeys (Sherwin, 1998) and fowl (Davis et al, 1999) prefer to eat in brighter illuminance may be because the process of eating for these birds is normally guided by vision. The visual field of fowl, and possibly turkeys, indicates that these species feed by visual guidance of the beak (Martin, 1999) (see Chapter 2, section 2.2.2.2). This may possibly explain the distinct preferences of these birds to feed at bright illuminances (200 lux) regardless of age, and the motivation of fowl to work 2.3 times harder for access to food illuminated at 200 lux than that at <1 lux (Prescott and Wathes, 2002). Further studies such as this could be used to assess the strength of these illuminance observed preferences for ducks and turkeys.

5.5.5 Conclusions on the illuminance preferences of ducks and turkeys

Ducklings and turkey poults showed different preferences for illuminance, and these differed to those displayed by fowl (Davis et al, 1999), possibly indicating different illuminance requirements. Ducklings preferred to spend least time in <1 lux and most in 6, 20 and 200 lux. The survey detailed in Chapter 4 (Table 4.3) shows that whilst the lower illuminances of this preferred range are often catered for in commercial duckling houses, the higher illuminances are often not. These preferences indicate that ducklings prefer to have access to illuminances that are lower than the RSPCA recommendation of a minimum of 20 lux (RSPCA, 1999a) as well as much higher illuminances. Another interpretation of these results would be that the provision of any illuminance of 6 lux or greater would satisfy the birds' preference for light illuminance.

The turkey poults showed an overall preference for 200 lux at two weeks of age, and for illuminances ≥20 lux at six weeks. These findings compare favourably to the recommendations of the RSPCA to provide turkey poults with a minimum of 20 lux

(1999b). However, the results of the survey (Chapter 4) show that such high illuminances are rarely used commercially due to the increased risk of injurious pecking. The FAWC (1995) recommendation of mean illuminances of 5 lux is contrary to the preferences of the birds, particularly at two weeks of age; although FAWC do advocate brighter illuminances if practical. These results have implications for welfare, as provision of illuminances that satisfy the birds' preference are associated with increases in injurious pecking and aggression (Manser, 1996). Beak trimming apparently allows turkey poults to be reared in higher illuminances, although the consequences of beak trimming may have significant implications for welfare (Gentle, 1986; Hughes and Gentle, 1995). If this welfare compromise is deemed unacceptable, it will be important to investigate other methods of reducing injurious pecking in poultry. As injurious pecking is not considered a major welfare concern in non-aggressive breeds of ducks, such as the Pekin, (Wilson, 2000, personal communication) ducklings are not bill-trimmed, and this welfare dilemma does not apply for ducklings reared in the UK.

These results alone do not prescribe the optimum illuminance for ducklings and turkeys, but they do imply that some variation in the ambient illuminance around a poultry house to provide a range of light environments might benefit the welfare of these poultry species. This would be in accordance with their preferences for a range of illuminances in which to perform various behaviours. Prescott and Wathes (2003) suggest that as long as the areas of different illuminance are large enough, this should not increase the risk of smothering that sometimes occurs in small areas of bright light. Alternatively, the variation in illuminance could be provided temporally. Additionally, these results do not answer the question as to whether the birds entered a particular illuminance to perform a behaviour or if the illuminance environment induced a certain behaviour to occur once it was entered. This may be resolved by the observation of the birds' behavioural time budgets in fixed illuminance environments. However, there may be some welfare concerns with rearing birds over a seven week period in relative darkness (<1 lux) or turkeys in 200 lux.

The identification of an illuminance preference is an important first step in determining optimum light conditions. However, further work is required before any recommendations can be made as to the optimum illuminance, or range of illuminances, for ducklings and turkey poults. Preference testing alone cannot provide evidence as to

the strength of a preference or aversion. Introducing a cost to choosing a particular environment can relate the amount an animal is prepared to pay to the strength of its motivation for that environment (Dawkins, 1990). Further studies, adopting different behavioural techniques should also be carried out in order to assess the findings of these investigations so that attempts can be made to understand the underlying mechanisms for the behavioural effects found in this study. This would enable future recommendations to be based on the birds' visual abilities, behaviour and preferences.

Chapter 6:

General Discussion

6.1 The context and objectives of this thesis

One of the consequences of rearing poultry species in environmentally-controlled housing is that the light environment is often provided by artificial light sources. These are manipulated to provide photoperiods, illuminances and colour balances that differ greatly from the range of natural light environments in which the progenitor species of domestic ducks and turkeys evolved. Current poultry lighting systems are largely based on human visual abilities and designed to meet criteria set for production, cost, inspection and behavioural modification. These requirements do not necessarily accommodate the visual abilities of the birds reared or the visual information they need to perform normal behaviours. Additionally, the light conditions under which many poultry are reared have been criticised on welfare grounds as it has been suggested that they may contribute to the aetiology of some significant poultry welfare concerns, such as lameness, injurious pecking and eye abnormalities (see Chapter 2, section 2.3).

Based on current understanding, guidelines for the welfare of poultry have been made that include recommendations for the provision of lighting (Chapter 2, Table 2.3). However, this information has been largely based on studies on domestic fowl. Further progress in the welfare of farmed ducks and turkeys requires more species-specific information. These birds have different ecological backgrounds and thus their requirements for light may differ from each other, possibly making the extrapolation of results from studies in domestic fowl inappropriate. In acknowledgement of this, recommendations have been made for research into the preferences of poultry species for various aspects of lighting and the requirements for light for different activities (FAWC, 1995; Manser, 1996). Undermining the aims of these welfare guidelines and recommendations is a fundamental problem that light measurement in poultry housing is not standardised (Prescott et al, 2003). Further, a second problem is the measurement of the light environment for non-human species that have different visual systems and which may therefore perceive light differently.

The overall aim of this thesis was to address the paucity of knowledge on how domestic ducks and turkeys perceive their light environment, with the intention of providing

information that may aid the measurement of illuminance as perceived by these species in commercial and experimental housing. A further aim was to gain a better understanding of the behavioural requirements of these birds for illuminance by investigating the preferences of growing ducklings and turkey poults for different illuminances in relation to their age and behaviour. These are some initial first steps that have been highlighted as important for further work to build on, with the long-term goal of optimising the light environment in duck and turkey housing.

6.2 Summary of findings and their implications

Whilst similar studies to those detailed in Chapters 3 and 4 have been undertaken for domestic fowl, the application of these methods to ducks and turkeys is novel. Previous studies have investigated the illuminance preferences of turkeys, but the experimental design adopted in Chapter 5 addressed some of the limitations of those studies highlighted by their authors; e.g. the inability to observe turkey behaviour in virtual darkness (<1 lux) (Sherwin, 1998), and the lack of combined testing of preferences for illuminance with observations of bird behaviour (Thompson, 2001). The use of a free-choice test to assess illuminance preferences of Pekin ducks, is to the author's knowledge, also novel.

6.2.1 The spectral sensitivity of domestic ducks and turkeys

The spectral sensitivity of domestic ducks and turkeys was determined using a psychophysical test. The results of these experiments provide behavioural evidence that domestic ducks and turkeys have similar but subtly different spectral sensitivities to each other, and that both species are able to perceive wavelengths spanning a broad range of the spectrum from λ=360 nm (in the UV_A part of the spectrum) to λ=694 nm (in the red range). However, ducks were found to be less sensitive to UV_A radiation than turkeys. This evidence for the reduced UV_A sensitivity in the duck (Chapter 3, Figures 3.8, 3.9 and 3.11) supports the microspectrophotometry results of Jane and Bowmaker (1988), who had suggested that ducks would be relatively insensitive to UV_A light, as the ocular media of the duck eye strongly absorbs wavelengths in that part of the spectrum, with transmission falling to 50% at λ=370 nm and 1% at λ=340 nm. In comparison, the ocular media in the turkey eye transmits UV_A wavelengths down to λ=315 nm, with 50% transmission occurring at 358 nm (Hart et al. 1999), suggesting a

greater sensitivity to UV_A wavelengths that is supported by the findings of the present study. In addition, ducks and turkeys were also shown to have similar spectral sensitivities to domestic fowl (Prescott and Wathes, 1999a) but quite different to humans, when tested under the same conditions and in comparison with the CIE standard human spectral sensitivity curve (1983) (Chapter 3, Figure 3.12). The human spectral sensitivity curve determined in this study is in good agreement with the results of previous studies in humans and primates (Sperling and Harwerth, 1971; Nuboer, 1986), which provides external validation of the method used in this study.

These results have a number of implications for the rearing of these poultry species under artificial lighting in commercial housing. The light sources typically used in duck and turkey housing (see Chapter 4) have a very different spectral power distribution to daylight and often lack UV_A wavelengths (see Figure 4.1). Whilst there is no evidence that the absence of particular wavelengths affects the normal development of the eye (Brenner et al, 1983), housing birds under lighting of inappropriate colour balances may deny these birds the use of the full range of their colour visual abilities, and may also prevent them from perceiving and using visual cues transmitted by certain wavelengths which may be of importance to them.

The functional significance of colour vision in some parts of the spectrum has not been determined (Honkvaara et al, 2002). However, a number of possible roles for UV_A perception in birds have been suggested (Bennett and Cuthill, 1994; Derrington, 2002). Although the results of this study do not suggest how ducks and turkeys may use this visual ability, when the evidence from other studies is considered alongside these results, they do support the suggestion that the provision of UV_A–supplemented light for turkeys may be beneficial to their welfare. Turkeys have been shown to have a preference for UV_A–supplemented fluorescent lighting to lighting without UV_A (Moinard and Sherwin, 1999), and markings in the plumage of these birds are visible under UV_A light (Sherwin and Devereux, 1999). In addition work by Lewis et al (2000) and Moinard et al (2001) has also indicated that supplementary UV_A lighting may have a role in reducing injurious pecking amongst male turkeys in combination with visual barriers and straw bales as enrichments. The role of UV_A vision in ducks is not as clear, and no literature suggests that it is used in social signalling or foraging. Indeed, behavioural studies have shown that taste and tactile cues can be used exclusively by these birds in food selection (Martin and Lett, 1985; cited by Jane, 1986). Whether

UV_A–supplemented lighting would be beneficial to ducks in commercial housing is currently unknown. Therefore, the role of UV_A vision in ducks and its possible benefits in a commercial context, if any, should be investigated further as the results of this study show that ducks do possess this visual ability, although to a lesser extent than turkeys.

6.2.2 The calculation of perceived illuminance for ducks and turkeys

In Chapter 4, estimates of the perceived illuminances for ducks and turkeys were calculated for the different light sources used in commercial housing, using the spectral sensitivity data determined in Chapter 3. This was undertaken as the validity of using the lux unit to describe and measure illuminance for animals which have a different spectral sensitivity to humans has been previously questioned (Nuboer et al, 1992). From the results of these studies it can be concluded overall that the lux unit, which is based on the CIE standard human spectral sensitivity curve (1983), is not an appropriate unit for describing the illuminance perceived by a duck or turkey. Nuboer et al (1992) and Prescott and Wathes (1999a) also found this to be the case for domestic fowl, which have a similar spectral sensitivity to ducks and turkeys.

From the results, it is concluded that ducks and turkeys will perceive the illuminance from the light sources typically used in commercial housing in a similar way to each other (Table 4.6). For example, these results imply that both domestic ducks and turkeys will perceive the illuminance from an incandescent lamp to be approximately 20% greater than that perceived from a fluorescent tube lit to the same lux unit. This perception was shown to alter slightly depending on the different types of fluorescent lamps due to the different phosphor mixes used by manufacturers. These results show that it is now essential for experimenters investigating the effects of different light sources and wavelengths on ducks and turkeys to consider the spectral sensitivity of these birds and how they perceive different light environments, if they are not to confound illuminance and wavelength. Using the spectral sensitivity data determined in Chapter 3 it is now possible to equate light environments and treatments with a known spectral composition for ducks and turkeys so that this interaction does not occur. This will enable studies to assess the effects of wavelength and illuminance on these birds, independently of each, as has been employed in studies on domestic fowl (Jones et al, 1999; 2001; Perkins, 2001; Kristensen et al, 2002; 2003) using the *c*lux unit derived by

Prescott and Wathes (1999a). Such an application of these results could greatly aid the progress of understanding the effects of these aspects of lighting on the production, health, behaviour and welfare of domestic ducks and turkeys.

Based on the findings of this study, the illuminance perceived by ducks and turkeys in commercial houses illuminated by different light sources to the same lux, could vary by approximately 20% (Table 4.6). Therefore, compliance with welfare codes and recommendations that state a minimum illuminance, without specifying light source type, will result in houses being illuminated to different levels. The practicalities of accounting for this in the standards and its application on a poultry farm are not simple. This is because the lack of standardised methods for light measurement and/or routine use of serviceable and calibrated light meters (see Chapter 4), hinders the accurate measurement of illuminance in poultry housing. Thus the use of these perceived illuminances will have limited practical application in a commercial context until this underlying problem is rectified.

The method used to calculate the perceived illuminances for ducks and turkeys in Chapter 4 follows that used to derive the *c*lux unit for domestic fowl (Prescott and Wathes, 1999a). However, it should be noted that this method requires a number of assumptions to be made which have been debated in the fields of photometry and vision research for a number of years (Jarvis, 2003, personal communication). These are:

1) that brightness perception is based upon the sum of the individual cone photoreceptor response, as determined by the number of photons per unit of time and not the radiant power of the light source; and

2) that in converting any perceived illuminances calculated into equivalent lux units, the maximum spectral luminous efficacy of radiation for photopic vision in humans (683 lumens/W), as used in the lux unit calculation, is assumed to be equivalent to that for the duck and turkey.

These assumptions require experimental confirmation, but have been made for practical purposes to allow illuminance measurements to be corrected for the spectral sensitivity of these birds rather than using the CIE standard human spectral sensitivity data (1983).

6.2.3 *The light environment in domestic duckling and turkey poult housing*

The main conclusions drawn from the findings of the survey (Chapter 4) are that the light environment in commercial duckling and turkey poults houses differs considerably from daylight. The use of low illuminances in some commercial houses, particularly for turkey poults, is discussed in relation to the results of the preference tests in section 6.2.4. The survey also found there was only a limited use of calibrated light meters to quantify illuminance and considerable differences between the estimates provided by farm managers/personnel and the illuminances measured. This finding is of particular concern given the specificity of some welfare recommendations and guidelines for minimum illuminances within duck and turkey housing. These results highlight the need for a standardised method of measurement and use of light meters to improve the monitoring and accurate assessment of illuminance in poultry housing.

6.2.4 *The preferences of ducklings and turkey poults for incandescent illuminances*

The relative preferences of ducklings and turkey poults were assessed in a free-choice test (Chapter 5). These results indicate that ducklings and turkey poults have different preferences for illuminance. At both two and six weeks of age ducklings spent most of their time in 6, 20 and 200 lux. This may indicate that these birds do not have a preference for a particular illuminance between 6 and 200 lux, or that ducklings prefer to have access to all three illuminances. Illuminance was shown to have a significant effect on the partitioning of behaviours amongst the treatments. At two weeks of age, moving and environmentally-directed pecking occurred most in 6, 20 and 200 lux; whereas at six weeks preening and feeding also occurred more often in these light environments. The results for turkey poults showed these birds had a more highly significant overall preference for 200 lux at two weeks of age, and for illuminances of 20 and 200 lux at six weeks. This change in overall preference was reflected in the partition of behaviours between the light environments. At two weeks of age, all behaviours occurred more in 200 lux; whilst at six weeks of age resting and perching were seen more often in 6, 20 and 200 lux with all other activities still observed more in 200 lux. These results imply that some variation in ambient illuminance, either spatially or temporally, to provide a range of illuminances might benefit the welfare of ducks and turkeys.

For both species, the dimmest illuminance (<1 lux) was the least preferred choice overall. It is concluded that these results do not necessarily imply an aversion to <1 lux, as the birds, particularly ducklings, were shown to spend some time in this illuminance. However, in the present study it is possible that the use of the <1 lux illuminance by the turkey poults may have been due to the birds moving through the compartment to access other illuminances or that the birds were monitoring their environment to see if conditions had changed (Nicol, 1997). To distinguish if this was a genuine preference or monitoring by the birds requires further studies to be undertaken.

The results of the light survey detailed in Chapter 4 indicate that whilst commercial duckling housing caters for the lower range of illuminances that ducklings prefer, the higher illuminances preferred are often not provided. In contrast, the survey showed that turkey poults are often reared in illuminances that are contrary to their preference for bright illuminances. These results have implications for duck and turkey welfare. The RSPCA (1999a) recommends a minimum illuminance of 20 lux for ducks, and the findings of these studies generally support this. However, the illuminances preferred by turkey poults are associated with increases in injurious pecking and aggression (Manser, 1996). Currently, low illuminances are often employed to control these behaviours, or beak trimming of birds is used, although the consequences of this procedure may have significant implications for welfare in turn (Gentle, 1986; Hughes and Gentle, 1995). Whether beak trimming should be employed so that illuminances can be increased to satisfy bird preferences and alleviate welfare concerns such as eye abnormalities (Siopes, 1983; 1984; Thompson and Forbes, 1999; Thompson, 2001) and lameness through (Hester et al, 1987) is a welfare compromise which is still debated. If this welfare compromise is deemed unacceptable, it will be important to investigate other methods of reducing injurious pecking in turkeys. These issues do not appear to concern duck production to such a great extent.

The preferences of ducklings and turkey poults differ to those displayed by domestic fowl in a similar test (Davis et al, 1999), and this may relate to their different ecological backgrounds and some differences in the anatomy of their eyes (Chapter 2, section 2.2). The preferences of ducklings for a range of illuminances, including dim light environments, may reflect the high proportion of rod photoreceptors in the duck retina and the low illuminance thresholds required for full dark adaptation to occur in these birds (Wells et al, 1975). Many duck species are crepuscular in the wild, whilst turkeys

and fowl are considered diurnal species. These findings, along with the results of the spectral sensitivity experiments, highlight the need for the requirements of individual species to be considered when designing lighting systems for poultry housing.

Further, these results demonstrate the care that needs to be exercised when interpreting the results of preference tests in general. Minority choices in simple preference tests should not be ignored, as they may still represent a choice for a resource important to the animal. For example, the <1 lux illuminance was the least preferred choice in the current study, but other studies show the benefits of fewer leg and eye problems through the use of periods of darkness for poultry (Classen, 1991; Gordon and Tucker, 1997). This raises the question of whether animals are able to select environments or resources that are conductive to their long-term benefits. For ducks that are slaughtered at seven weeks of age and turkeys which are often reared to 15 weeks (hens) or 20 weeks (stags) the concept of long-term fitness may be futile.

6.3 Further work

A number of avenues for further research have presented themselves from the results of these investigations.

The differences found between ducks and turkeys in their sensitivity to UV_A wavelengths raises interesting questions on how this visual ability is used by these species. Whilst there is some evidence to suggest that turkeys may use UV_A mediated cues in social recognition (Sherwin and Devereux, 1999; Lewis et al, 2000; Moinard et al, 2001), the role of this visual ability in feeding behaviour has not been formally investigated for turkeys or ducks. Experiments with redwings (*Turdus iliacus*) (Siitari et al, 1999) and black grouse (*Tetrao textrix*) (Siitari and Hovi, 2002) show that these species have preferences for UV_A reflecting food sources only when they are presented under UV_A lighting. Similar experiments could be conducted to indicate if UV_A cues played a role in the feeding behaviour of ducks and turkeys. By using the perceived illuminances for ducks and turkeys calculated in Chapter 4, it would be feasible to equate light sources with and without a UV_A component, so that a wavelength and illuminance interaction would not confound the results. Additionally, the use of these treatments at different illuminances could also be incorporated into the experimental design to further assess the feeding preferences of these birds.

A limitation of the free-choice preference test used in Chapter 5 is that it was not able to measure the strength of the preferences shown. Additional studies are therefore required to quantify this. Motivations that are shown to be weak may not need to be incorporated into proposals for the design of any new lighting systems for these species. As both ducks and turkeys used the <1 lux illuminance least in the current study, this may be an appropriate illuminance to test against a more preferred illuminance. Additionally, introducing a cost to access this illuminance would also be a way of distinguishing whether the turkey poults were monitoring their environment or had a genuine preference (Nicol, 1997). To assess these motivations, a methodology would need to be developed which is sensitive enough to detect weak motivations and also incorporates naturalistic behaviour. Possible options are the modification of the weighted door technique used by Jones (2002) to test the motivation of broiler fowl to seek fresh air after exposure to ammonia. Alternatively, an operant task such as training birds to peck a switch that provided a given illuminance for a designated period of time in return for a food reward could be used. A similar methodology was used by Savory and Duncan (1982/1983) to assess the preferences of fowl for light and dark. As ducks and turkeys were trained to complete an operant task for completion of the spectral sensitivity experiments, this method could be a feasible option.

6.4 Conclusions and recommendations

From the results of these experiments it is only possible to make some tentative recommendations for specifying appropriate light environments for ducks and turkeys. Differences in UV_A perception and illuminance preferences between ducks and turkeys show the importance of providing species-specific lighting in housing. The results of the spectral sensitivity experiments support the suggestions of other studies that full spectrum or UV_A-supplementary lighting may be advantageous for turkeys. It is important that future research identifies the role of UV_A vision in ducks before its use is advocated. The general use of light sources of restricted spectral power distributions in housing should be limited, as it may prevent ducks and turkeys from using the full range of their colour visual abilities.

It is recommended that the use of calibrated light meters by trained staff, using a standard method of measurement becomes more common in poultry housing. This could benefit the welfare of ducks and turkeys by enabling producers to more closely

follow welfare codes and recommendations aimed at improving the visual environment of these birds.

It is not possible yet to prescribe an optimum illuminance for ducklings and turkey poults, but the results of the preference tests generally support those recommended in the current welfare codes and guidelines. As the issues concerning the control of injurious pecking have yet to be determined, the question of a mean illuminance for turkeys is not simply resolved. As pointed out by Dawkins (1997), the answers to complicated questions concerning welfare and behaviour should not be over-simplified. However, for non-aggressive breeds of ducks the recommendation of this thesis is that relatively bright illuminances with an adequate dark period can be used to satisfy their preferences. It is also suggested that some variation in the ambient illuminance around a duck or turkey house to provide a range of light environments might benefit the welfare of these poultry species. This would be in accord with the birds' preferences for a range of dim and brighter illuminances in which to perform various behaviours.

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Ist ofAbbreviations

ANOVA	Analysis Of Variance
BUT	British United Turkeys
CCT	Correlated Colour Temperature
CIE	Commission International de l'Éclairage
D	Diopters
DEFRA	Department for the Environment, Food and Rural Affairs (previously MAFF)
FAO	Food and Agriculture Organisation of the United Nations
FAWC	Farm Animal Welfare Council
FL^c	Compact Fluorescent luminaires
FL^t	Fluorescent tube luminaires
GEC	General Electrical Company
IN	Incandescent luminaires
IOP	Intra-Ocular Pressure
L:D	Light:Dark (hours of each per 24 h period)
LED	Light-emitting diode
LWS	Long Wavelength Sensitive
MAFF	Ministry of Agriculture, Fisheries and Food (now DEFRA)
MWS	Medium Wavelength Sensitive
PF	Photon Flux
PND	Posterior Nodal Distance
RSPCA	Royal Society for the Prevention of Cruelty to Animals
SPD	Spectral Power Distribution
SSPD	Standardised Spectral Power Distribution
SWS	Short Wavelength Sensitive
UK	United Kingdom
USA	United States of America
UV	Ultraviolet (100-380 nm)
UV_A	Ultraviolet Alpha wavelengths (315-380 nm)
UV_B	Ultraviolet Beta wavelengths (280-315 nm)
UV_C	Ultraviolet Gamma wavelengths ($200 < \lambda < 280$ nm)
UVS	Ultraviolet Sensitive
VS	Violet Sensitive

λ	Lamda or wavelength
λ_{cut} nm	cut-off wavelength – the wavelength of intercept between the line tangent to the absorbance curve at 50% transmission and maximum absorbance
λ_{max} nm	maximum absorbance of wavelengths

Appendix I

The individual and mean absolute spectral sensitivity thresholds for ducks, turkeys and humans.

The individual and mean absolute thresholds obtained ducks, turkeys and humans in the spectral sensitivity experiment (Chapter 3) are given in Tables I.1, I.2 and I.3.

Table I.1 The individual and mean absolute spectral sensitivity thresholds for ducks.

Threshold Sensitivity (photons s^{-1} x 10^{10})	**Wavelength (nm)**												
	326	**360**	**380**	**415**	**450**	**486**	**508**	**544**	**577**	**600**	**633**	**656**	**694**
duck1		39.44	10.53	7.75	1.59	2.35	2.46	1.49	1.25	1.93	1.65	3.38	10.51
duck2		34.80	7.42	7.62	1.88	1.24	2.62	1.44	1.19	1.93	2.86	4.02	8.05
duck3	*46.21	27.84	5.75	5.88	2.61	1.35	2.62	1.52	1.45	1.68	1.20	3.59	9.39
duck4		30.16	14.69	7.62	1.74	1.24	2.13	1.35	2.23	2.13	1.35	4.02	6.48
duck5		37.12	13.32	6.15	1.23	1.72	1.54	0.98	1.12	2.13	1.35	3.59	13.86
duck6					**2.17**		**2.29**	**1.93**			**3.67**		
duck7		37.12	9.79	8.29	1.45	2.51	2.62	1.58	1.41	3.71	1.49	5.07	18.56
duck mean (SEM)		34.41	10.24	7.22	1.81	1.74	2.33	1.47	1.44	2.25	1.94	3.95	11.14
		(1.84)	(1.39)	(0.40)	(0.18)	(0.23)	(0.15)	(0.11)	(0.17)	(0.30)	(0.36)	(0.25)	(1.80)

* Absolute threshold value for duck 3 at λ=326 nm not included in the calculation of the mean.

Data in **bold** are thresholds collected before duck 6 died; these were included in the calculation of the mean.

Table I.2 The individual and mean absolute spectral sensitivity thresholds for turkeys.

Threshold Sensitivity (photons s^{-1} x 10^{10})	**Wavelength (nm)**												
	326	**360**	**380**	**415**	**450**	**486**	**508**	**544**	**577**	**600**	**633**	**656**	**694**
turkey1	*33.61	20.88	4.77	8.56	2.32	1.36	2.13	0.98	1.54	3.29	1.92	4.02	16.10
turkey2		16.24	4.41	6.55	2.90	1.35	2.46	1.44	1.52	2.71	1.92	2.11	15.43
turkey3		27.84	5.75	6.28	1.16	2.04	2.62	1.44	1.13	2.71	0.90	3.38	14.53
turkey4		13.92	3.92	7.49	1.16	1.57	2.62	1.52	1.41	3.48	2.86	3.59	18.56
turkey5						**1.32**	**2.46**	**1.93**		**3.71**			
turkey6		16.24	4.29	8.02	1.74	1.72	2.29	1.58	1.75	3.87	3.26	3.80	22.80
turkey7		23.20	2.70	7.75	2.32	1.88	1.57	1.35	0.86	3.09	1.24	3.17	10.51
turkey mean (SEM)		19.72 (2.14)	4.28 (0.41)	7.44 (0.36)	1.93 (0.29)	1.61 (0.11)	2.31 (0.14)	1.46 (0.11)	1.37 (0.13)	3.27 (0.19)	2.02 (0.37)	3.35 (0.28)	16.32 (1.68)

* Absolute threshold value for turkey 1 at λ=326 nm not included in the calculation of the mean.

Data in **bold** are thresholds collected before turkey 5 was removed from the experiment; these were included in the calculation of the mean.

Table I.3 The individual and mean absolute spectral sensitivity thresholds for humans.

Threshold Sensitivity (photons s^{-1} x 10^{10})	Wavelength (nm)												
	326	**360**	**380**	**415**	**450**	**486**	**508**	**544**	**577**	**600**	**633**	**656**	**694**
human1			17.14	14.31	1.59	3.60	1.55	0.98	2.23	1.68	2.24	6.13	12.30
human2			23.26	13.10	2.03	2.35	2.78	1.07	2.60	2.13	3.87	6.34	19.90
human3			46.52	14.98	2.49	2.98	3.11	1.93	1.86	2.44	3.87	12.26	33.99
human4			24.49	13.10	3.48	2.98	2.78	1.67	2.23	2.86	5.09	14.80	39.13
human5			46.52	13.50	3.19	4.23	1.96	1.93	2.79	2.86	5.50	10.57	33.99
human6			***1.10**	12.83	2.32	3.76	2.29	1.35	1.69	1.93	4.89	7.40	19.90
human7			20.82	13.91	1.88	2.82	2.13	1.28	1.56	1.59	3.47	8.03	21.02
human mean (SEM)			29.79 (5.39)	13.68 (0.31)	2.43 (0.26)	3.25 (0.26)	2.37 (0.21)	1.46 (0.15)	2.14 (0.19)	2.21 (0.21)	4.13 (0.42)	9.36 (1.34)	25.75 (4.04)

* Absolute threshold value for human 6 at λ=380 nm; not included in the calculation of the mean.

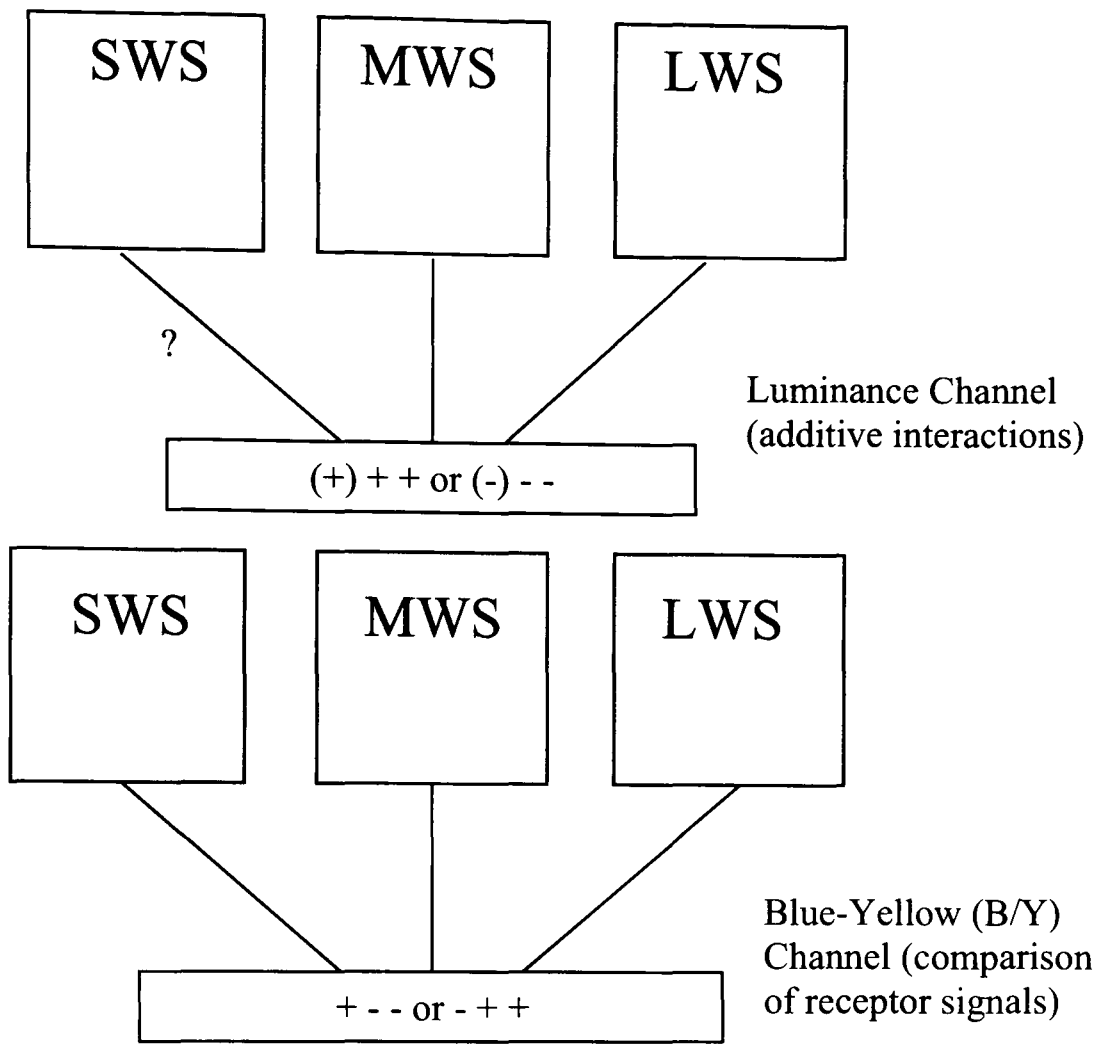
Appendix II:

A brief explanation of opponent-process theory in trichromatic colour vision.

Normal human observers are considered to be trichromatic, not just because they possess three types of single cones in their retina, but also because they require the three spectral colours of blue, green and red to match any light of a given spectra (Kelber et al, 2003). However, human observers in studies investigating subjective experiences of hue often act as if there are four rather than three "primary" colours: blue, green, red and yellow. Certain combinations of these colours are never reported in such studies. For example, a colour would not be described as yellowish-blue. Based on this, Hering (1872; cited by Coren et al, 1979) developed the theory of opponent-processing, arranging these four "primaries" in opposing pairs. One pair would signal the presence of blue or yellow, the other red or green (Coren et al, 1979). Results from electrophysiological and psychophysical tests have provided supporting evidence for this theory (Hurvich and Jameson, 1974; cited by Bartleson, 1984). Such results show that the neural processing of cone receptor signals is subject to both the excitatory and inhibitory influences by signals from other interacting cones.

Figure II.1 shows a general model of how the trichromatic cone system in humans may produce an opponent-process neural response. Models of human vision may vary in detail, but are all based on the assumption that human photopic vision is based on three classes of cone cells which each contain a visual pigment of different spectral absorption, resulting in short wavelength-sensitive (SWS), medium wavelength-sensitive (MWS) and long wavelength-sensitive (LWS) cones. These signals from the cones respond in either a synergistic or antagonistic manner when neural processing to encode hue information occurs in the visual cortex (Nuboer, 1986).

In simplified terms, wavelength discrimination is achieved through the integration of excitatory and inhibitory synaptic effects that originate from the light stimulation of the three cone cells, each with different spectral sensitivities (Nuboer, 1986). Light of a certain wavelength composition is absorbed by the appropriate types of cone cell; short wavelength-sensitive (SWS), medium wavelength-sensitive (MWS) and long wavelength-sensitive (LWS) cones. Synaptic signals and processing, resulting from the



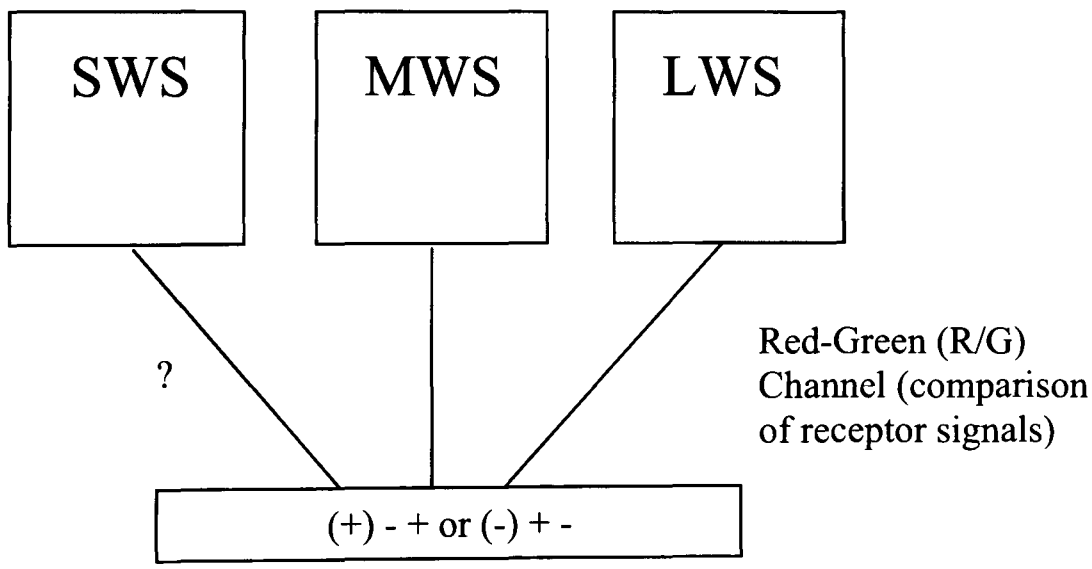


Figure II.1 A general model of how the trichromatic cone system in humans may produce an opponent-process neural response. SWS = short wavelength-sensitive (blue) cone; MWS = medium wavelength-sensitive (green) cone, LWS = long wavelength-sensitive (red) cone; + = excitation; - = inhibition.

Source: Nuboer (1986).

excitation of some cone cells is transported through the layers of the retina and by the optic nerve fibres from the eye to the *lateral geniculate nuclei* and then up to the visual cortex (De Valois and De Valois, 1975; cited by Coren et al, 1979). During this post-retinal processing the visual information is transformed from the trichromatic processing mechanism to the opponent processing mechanism. These signals have either excitatory affects on the synaptic signals from some types of cones and/or inhibitory affects on the signals from others. This gives rise to the two opponent channels: a long wavelength-sensitive (LWS) versus a medium wavelength-sensitive (MWS) channel, and a short wavelength-sensitive (SWS) versus a medium wavelength-sensitive (MWS) or a long wavelength-sensitive (LWS) or the two combined (MW + LW) channel. These two chromatically opponent channels are frequently referred to as the red-green and blue-yellow channels (Bartleson, 1984; Kaiser, 1984). A third channel accounts for luminance perception where the integration of either excitatory or inhibitory synaptic signals from cones leads to the detection of luminance contrasts (Bartleson, 1984; Kaiser, 1984; Nuboer, 1986).

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Appendix III:

Determining the minimum accuracy of panel choice by ducks and turkeys in the spectral sensitivity experiment.

The following description details how the minimum percentage of accuracy with which ducks and turkeys chose panels in the spectral sensitivity experiments (Chapter 3) was determined. The amount of work a bird had to do for a successful discrimination at a given illuminance depended on the frequency with which the panel changed position. For example, the minimum work required of a bird would be if the assignment of the lit panel changed after each reward as follows:

$$A \rightarrow B^{1} \rightarrow A^{2} \rightarrow B^{3} \rightarrow A^{4} \rightarrow B^{5}$$

$^{1, 2, 3, 4, 5}$ = number of changes of panel position

According to the criteria set (see Chapter 3, section 3.3.6 Experimental protocol), the minimum number of pecks a bird would have to perform for this sequence of presentations to be a successful discrimination would be 24 pecks to the correct/lit panel (4 pecks for each of the six presentations), with no more than four incorrect pecks to the dark panel by the time the panel position had changed five successive times (two pecks to the incorrect/dark panel being allowed on two occasions in a sequence). Thus a minimum of 85.71% of pecks had to be made to the correct/lit panel for a bird to obtain a successful discrimination. Had the birds been selecting the panels by chance, this would have fallen to around 50%. However, during the experiment it was rare that such a short sequence of presentations occurred in order to produce five changes of panel position. A more typical sequence is shown below:

$$BBB \rightarrow AA^{1} \rightarrow B^{2} \rightarrow AA^{3} \rightarrow BBB^{4} \rightarrow A^{5}$$

$^{1, 2, 3, 4, 5}$ = number of changes of panel position

For this sequence of presentations to be counted as a successful discrimination, a bird had to perform 48 pecks to the correct/lit panel in total, and make no more than four incorrect pecks to the dark panel. Thus, a minimum of 92.31% of pecks had to be made

to the correct/lit panel by a bird to obtain a successful discrimination. These simple calculations show the birds were not pecking by chance at the illuminated stimuli.

Appendix IV

The illuminances and colour temperatures for a range of natural and artificial light environments.

Illuminances for a range of natural and artificial light environments

Table IV.1 gives a range of typical illuminances encountered in various natural and artificial light environments.

Table IV.1 Typical illuminances for various light environments.

Location	Illuminance (lux)
Direct sun	100,000
Overcast sky	1,000
TV Studio	1,000
Business Office	250
Laying hen houses [a]	~20
Good street lighting	20
Twilight	10
Broiler house [a]	~3
Turkey house [b]	1-4
Deep twilight	1.0
Full moon	0.1
Starlight	0.001
Overcast night	0.0001

Sources: [a] Prescott and Wathes (1999); [b] FAWC (1995); the rest Jarvis, J. (2000).

The colour temperature of light sources

To indicate its colour characteristics, light is often said to have a correlated colour temperature (CCT), which is measured in Kelvins (°K). This refers to the radiation emitted from a light source as having an almost identical colour appearance to that of a black body (a theoretical object that absorbs all radiation falling on it and reradiates that

energy) (Duncan, 1990). The absolute temperature associated with this matching black body radiant emittance is then given as the correlated colour temperature of the light source (Prescott et al, 2003). This is a useful way of classifying nominally "white" light sources which differ in their actual appearance. Light sources with a low CCT are usually described as having a "warm", yellow-orange appearance. Those with a high CCT are considered to appear "cooler" and bluer. If the energy output of a light source is increased its colour temperature is changed. This explains why a high wattage light source is less yellow than a low wattage source (Panoptic Information sheets, 2003).

Table IV.2 The colour temperature of a range of light sources.

Location	Colour temperature (°K)
Daylight	6500
'Cool white' fluorescent lamp*	4300
'Warm white' fluorescent lamp*	3000
Incandescent tungsten filament lamp	2850
Compact fluorescent lamp*	2700
Sunlight at sunset	2000
Candle flame	1800

Source: Prescott et al (2003).
* Colour temperature will vary between manufacturers and in response to the colour characteristics of the different phosphor mixes used.

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Appendix V

Method for calculating perceived illuminance for ducks and turkeys.

The following description details how the perceived illuminances for ducks and turkeys given in Chapter 4 were calculated.

The spectral power distribution (SPD) of the light sources to be corrected was measured in $\mu W\ cm^{-2}\ nm^{-1}$ at 5 nm intervals between 300 and 700 nm. In the following equations the SPD of a light source will be referred to as P_i. The SPD data of the light sources was first converted to a photon flux (PF) [denoted N_i] for each wavelength:

$$N_i = \frac{P_i \lambda}{hc} \qquad (1)$$

where λ is the wavelength, h is Planck's constant and c is the speed of light.

This PF is then converted into a standardised SPD (SSPD) denoted by S_i

$$S_i = N_i \frac{hc}{\lambda_s} \qquad (2)$$

where λ_s is a standard wavelength, taken here as 700 nm. This was chosen as 700 nm is the maximum of the range of wavelengths sampled, although any wavelength could have been used. The SSPD data therefore has the same units as the original SPD data, are taken to be representative of the perceived "brightness" of the light source. The rationale for this calculation is discussed in Chapter 4, sections 4.3.2 and 4.5.2.

The SSPD data for each light source was then multiplied by the CIE standard human spectral sensitivity data (1983) (human SS CIE data) for each wavelength [H_i^{cie}] and the sum across the wavelength range calculated, denoted by B_{cie}.

$$B_{cie} = \sum_i S_i H_i^{cie} \qquad (3)$$

These B_{cie} values, one for each light source, are equivalent (but not equal) to the perceived brightness for a standard human CIE observer for that light source. These values technically have units of $\mu W\ cm^{-2}$, although are best considered to be an arbitrary perceived brightness unit.

One light source was then chosen to make all the other light sources iso-luminant to. For this study, the most common light source found in the duckling and turkey poult

housing was selected, i.e., the 60W incandescent bulb (GEC, pearl). This was done by calculating a correction factor [$F_{light\ source}$] for each light source:

$$F_{light\ source} = \frac{B_{cie}^{60W\ incandescent}}{B_{cie}^{light\ source}} \qquad (4)$$

For each light source this factor was applied to give an iso-luminant SSPD [$S_i^{iso\text{-}luminant}$], with reference to the human SS CIE data.

$$S_i^{iso-luminant} = \frac{F_{light\ source} S_i H_i^{cie}}{H_i^{cie}} \qquad (5)$$

The iso-luminant SSPD therefore has the same units as the original SPD.

The values for the iso-luminant SSPD data for each light source were then multiplied by the duck [D_i], turkey [T_i] or human [H_i] relative spectral sensitivity data (as determined in Chapter 3) and the sum across the wavelength range calculated, denoted by B_{duck}, B_{turkey} or B_{human}.

$$B_{duck} = \sum_i S_i^{iso-luminant} D_i \qquad (6)$$

$$B_{turkey} = \sum_i S_i^{iso-luminant} T_i \qquad (7)$$

$$B_{human} = \sum_i S_i^{iso-luminant} H_i \qquad (8)$$

These summed values are equivalent to the brightness perceived by a duck, turkey and human when the light sources are iso-luminant with reference to the CIE standard human spectral sensitivity curve (1983).

To obtain the ratio [R] of duck, turkey or human perceived illuminance to measured illuminance (Chapter 4, Table 4.5) these B_{duck}, B_{turkey} or B_{human} values for each light source were divided by the $B_{cie}^{60W\ incandescent}$ reference value

$$R_{duck}^{light\ source} = \frac{B_{duck}^{light\ source}}{B_{cie}^{60W\ incandescent}} \qquad (9)$$

$$R_{turkey}^{light\ source} = \frac{B_{turkey}^{light\ source}}{B_{cie}^{60W\ incandescent}} \qquad (10)$$

$$R_{human}^{light\ source} = \frac{B_{human}^{light\ source}}{B_{cie}^{60W\ incandescent}} \qquad (11)$$

Each ratio can then be used as a correction factor and multiplied by any illuminance measurements taken for that light source in the lux unit to give a corrected unit for the illuminance perceived by the subject. This assumes some similarity of the maximum spectral luminous efficacy between species which is discussed in Chapter 4, section 4.5.2.

To obtain the ratio of duck [Dr], turkey [Tr] or human [Hr] perceived illuminance of one light source (B) compared to another (A), when the light sources are iso-luminant with reference to the CIE standard human spectral sensitivity curve (1983)

$$Dr_{light\ source\ A}^{light\ source\ B} = \frac{B_{duck}^{light\ source\ B}}{B_{duck}^{light\ source\ A}} \qquad (12)$$

$$Tr_{light\ source\ A}^{light\ source\ B} = \frac{B_{turkey}^{light\ source\ B}}{B_{turkey}^{light\ source\ A}} \qquad (13)$$

$$Hr_{light\ source\ A}^{light\ source\ B} = \frac{B_{human}^{light\ source\ B}}{B_{human}^{light\ source\ A}} \qquad (14)$$

Then the illuminance of light source A, measured in lux can be multiplied by this ratio to get the measured illuminance which makes light source A iso-luminant to light source B. In this study, this was done by taking light source B to be the 60W incandescent bulb (GEC, pearl) (see Chapter 4, Table 4.6).

Appendix VI

The iso-luminant standardised spectral power distributions of the light sources measured in duckling and turkey poult housing, with reference to the CIE standard human spectral sensitivity curve (1983).

Table VI.1 shows the iso-luminant standardised spectral power distributions (iso-luminant SSPD) (at 5 nm intervals) of the eight artificial light sources that were measured in Chapter 4, and used to calculate the perceived illuminances for ducks, turkeys and humans.

Table VI.1 The standardised spectral power distributions of the eight artificial light sources measured in duckling and turkey poult housing and daylight, when made iso-luminant with reference to the CIE standard human spectral sensitivity curve (1983).

nm	Incandescent, 60W, GEC	Incandescent, 100W, GEC	Incandescent, 25W, GEC	Incandescent, 60W, Marathon	Compact Fluorescent, 11W, Phillips	Fluorescent Tube, 40W, GEC	Fluorescent Tube, 11W, Phillips	Fluorescent Tube, 20W, Osram	Daylight
300	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
305	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
310	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
315	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
320	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
325	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
330	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
335	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
340	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
345	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
350	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
355	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
360	4.79	8.56	4.41	4.10	25.64	12.66	8.93	2.10	23.50
365	5.41	9.18	5.62	5.23	161.01	26.70	21.44	24.34	25.83
370	6.39	10.12	7.51	5.26	29.01	9.92	8.44	3.80	26.88
375	7.20	10.90	8.04	6.98	15.25	9.72	7.73	4.48	24.14
380	7.53	11.26	8.84	7.79	18.26	10.13	8.08	7.78	30.02
385	8.35	12.05	9.56	9.36	12.76	10.76	8.57	10.78	29.07
390	9.67	13.30	9.55	9.89	9.61	12.25	9.74	14.03	31.43
395	10.21	13.84	9.29	9.76	7.96	13.50	10.70	16.55	33.01
400	10.79	14.42	9.89	10.34	42.02	50.07	30.17	39.79	48.05
405	11.85	15.43	10.96	11.41	148.26	108.76	87.42	94.10	50.59

Table VI.1(cont.) The standardised spectral power distributions of the eight artificial light sources measured in duckling and turkey poult housing and daylight, when made iso-luminant with reference to the CIE standard human spectral sensitivity curve (1983), continued.

nm	Incandescent, 60W, GEC	Incandescent, 100W, GEC	Incandescent, 25W, GEC	Incandescent, 60W, Marathon	Compact Fluorescent, 11W, Phillips	Fluorescent Tube, 40W, GEC	Fluorescent Tube, 11W, Phillips	Fluorescent Tube, 20W, Osram	Daylight
410	12.11	15.73	11.22	11.67	34.98	25.20	20.95	25.16	47.30
415	12.41	16.05	11.50	11.96	11.49	21.69	17.23	23.02	53.53
420	12.72	16.39	11.81	12.27	8.06	24.09	19.15	24.87	53.60
425	13.15	16.83	12.23	12.69	7.07	26.33	20.93	26.97	52.94
430	13.48	17.19	12.56	13.03	13.43	32.41	24.39	31.68	43.70
435	13.56	17.32	12.63	13.10	112.66	121.65	97.55	157.18	53.49
440	14.92	18.60	14.01	14.47	40.55	46.62	44.20	59.62	55.70
445	15.23	18.94	14.31	14.77	4.98	31.78	25.42	34.17	59.16
450	15.85	19.55	14.93	15.39	4.20	31.85	25.74	35.79	64.99
455	16.32	20.04	15.40	15.87	3.80	32.21	25.81	37.44	65.23
460	17.53	21.18	16.62	17.08	3.80	32.17	25.79	38.40	65.00
465	18.42	22.04	17.52	17.98	8.12	32.03	25.66	39.43	64.95
470	19.06	22.67	18.16	18.61	8.44	31.50	25.25	40.15	62.60
475	20.09	23.66	19.21	19.65	10.75	30.94	24.77	40.24	64.36
480	20.36	23.96	19.47	19.92	41.13	31.22	24.92	40.04	65.79
485	22.43	25.88	21.58	22.01	76.17	34.12	27.19	40.26	59.14
490	23.52	26.91	22.67	23.10	70.97	33.96	27.36	40.14	62.71
495	25.11	28.40	24.29	24.71	64.63	30.59	24.68	38.67	62.59
500	26.56	29.77	25.77	26.17	48.60	18.31	22.87	37.79	61.09
505	28.86	31.89	28.10	28.48	18.90	18.39	21.98	37.13	62.40
510	30.52	33.44	29.79	30.16	10.28	18.84	22.01	36.97	63.19
515	32.73	35.48	32.04	32.39	6.64	19.80	22.68	37.91	61.02
520	34.97	37.55	34.33	34.65	4.90	21.50	24.29	39.97	62.72

Table VI.1(cont.) The standardised spectral power distributions of the eight artificial light sources measured in duckling and turkey poult housing and daylight, when made iso-luminant with reference to the CIE standard human spectral sensitivity curve (1983), continued.

nm	Incandescent, 60W, GEC	Incandescent, 100W, GEC	Incandescent, 25W, GEC	Incandescent, 60W, Marathon	Compact Fluorescent, 11W, Phillips	Fluorescent Tube, 40W, GEC	Fluorescent Tube, 11W, Phillips	Fluorescent Tube, 20W, Osram	Daylight
525	37.23	39.64	36.63	36.94	7.56	24.19	27.06	43.59	63.50
530	40.14	42.31	39.60	39.87	27.51	27.95	31.25	49.48	66.40
535	42.69	44.65	42.19	42.44	61.47	33.25	38.23	57.60	66.29
540	46.03	47.72	45.61	45.82	81.32	40.83	53.88	68.47	63.18
545	48.60	50.09	48.23	48.42	93.23	75.84	74.38	63.42	65.63
550	52.33	53.49	52.03	52.18	82.84	67.32	70.78	52.98	67.33
555	55.44	56.34	55.21	55.33	68.65	69.08	70.06	58.27	68.16
560	59.30	59.86	59.15	59.23	45.31	78.84	76.98	71.50	66.55
565	63.66	63.83	63.60	63.63	32.15	88.89	84.51	82.43	65.66
570	67.48	67.33	67.50	67.49	24.10	96.87	90.22	85.91	64.49
575	71.43	70.94	71.54	71.49	58.80	113.38	97.42	89.50	65.22
580	76.08	75.17	76.29	76.18	92.25	117.40	101.89	89.97	67.02
585	81.09	79.72	81.41	81.25	97.24	109.22	102.47	89.16	66.50
590	84.81	83.11	85.21	85.01	99.16	106.64	102.54	90.08	62.75
595	89.31	87.21	89.81	89.55	100.03	101.97	99.75	83.70	64.91
600	94.42	91.86	95.03	94.72	100.21	95.85	95.42	73.13	65.97
605	100.02	96.95	100.76	100.39	104.97	87.79	90.45	61.59	67.75
610	104.05	100.62	104.87	104.45	138.29	79.67	94.50	105.98	67.08
615	108.92	105.05	109.85	109.38	132.23	70.90	83.57	93.30	65.48
620	114.51	110.12	115.56	115.03	115.39	64.56	73.23	81.75	67.07
625	121.24	116.22	122.45	121.84	119.85	58.90	67.52	70.88	64.85
630	127.22	121.65	128.57	127.89	123.95	52.96	61.11	61.43	64.09
635	132.92	126.84	134.40	133.65	93.18	46.96	51.51	52.67	65.51
640	138.53	131.93	140.13	139.32	63.57	40.61	44.58	44.65	65.80

Table VI.1(cont.) The standardised spectral power distributions of the eight artificial light sources measured in duckling and turkey poult housing and daylight, when made iso-luminant with reference to the CIE standard human spectral sensitivity curve (1983), continued..

nm	Incandescent, 60W, GEC	Incandescent, 100W, GEC	Incandescent, 25W, GEC	Incandescent, 60W, Marathon	Compact Fluorescent, 11W, Phillips	Fluorescent Tube, 40W, GEC	Fluorescent Tube, 11W, Phillips	Fluorescent Tube, 20W, Osram	Daylight
645	143.63	136.56	145.34	144.48	65.13	34.42	37.82	36.81	63.90
650	150.60	142.87	152.47	151.52	107.40	28.94	32.40	30.47	64.26
655	155.40	147.24	157.38	156.38	70.25	24.25	26.84	24.66	57.33
660	161.66	152.91	163.78	162.71	69.78	20.52	22.79	20.22	66.67
665	166.94	157.76	169.18	168.05	53.81	17.13	18.94	15.86	66.34
670	173.42	163.63	175.80	174.59	34.02	14.52	15.91	12.83	67.34
675	179.77	169.39	182.30	181.02	27.58	12.08	13.31	9.78	66.60
680	186.21	175.22	188.89	187.54	30.19	10.34	11.43	7.74	66.20
685	193.17	181.52	196.01	194.57	56.37	8.76	9.89	6.05	58.17
690	198.58	186.49	201.54	200.04	51.14	7.77	8.94	5.16	58.24
695	205.56	192.81	208.68	207.10	29.35	6.35	7.09	2.85	61.81
700	211.45	198.15	214.70	213.06	20.54	5.40	5.92	1.74	61.32

Appendix VII

The experimental design and allocation of the illuminance treatments for the preference test experiments.

The experimental design for each batch of ducklings and turkey poults preference tested in Chapter 5, showing the allocation of the illuminance treatments to the compartments is displayed in Tables VII.1-VII.4.

Table VII.1 The experimental design for each batch of ducklings at two weeks of age, showing the allocation of the illuminance treatments to the compartments.

Age	Batch	Compartment set	Flock	Days	Nominal illuminance in each compartment of the preference chamber (lux)			
					Compartment 1	Compartment 2	Compartment 3	Compartment 4
2 wks	1	1	2	1	6	<1	20	200
				2	<1	6	200	20
				3	200	20	<1	6
				4	20	200	6	<1
		2	1	1	<1	6	200	20
				2	6	<1	20	200
				3	200	20	<1	6
				4	20	200	6	<1
	2	1	3	1	200	<1	20	6
				2	<1	6	200	20
				3	6	20	<1	200
				4	20	200	6	<1
		2	4	1	<1	6	200	20
				2	20	200	6	<1
				3	6	20	<1	200
				4	200	<1	20	6

Table VII.2 The experimental design for each batch of ducklings at six weeks of age, showing the allocation of the illuminance treatments to the compartments.

Age	Batch	Compartment set	Flock	Days	Nominal illuminance in each compartment of the preference chamber			
					Compartment 1	Compartment 2	Compartment 3	Compartment 4
6 wks	1	1	2	1	200	<1	20	6
				2	6	20	<1	200
				3	20	200	6	<1
				4	<1	6	200	20
		2	1	1	200	<1	20	6
				2	20	200	6	<1
				3	<1	6	200	20
				4	6	20	<1	200
	2	1	3	1	<1	6	200	20
				2	6	20	<1	200
				3	200	<1	20	6
				4	20	200	6	<1
		2	4	1	200	<1	20	6
				2	6	20	<1	200
				3	<1	6	200	20
				4	20	200	6	<1

Table VII.3 The experimental design for each batch of turkey poults at two weeks of age, showing the allocation of the illuminance treatments to the compartments.

Age	Batch	Compartment set	Flock	Days	Nominal illuminance in each compartment of the preference chamber			
					Compartment 1	Compartment 2	Compartment 3	Compartment 4
2 wks	1	1	2	1	200	<1	20	6
				2	20	200	6	<1
				3	<1	6	200	20
				4	6	20	<1	200
		2	1	1	<1	6	200	20
				2	200	<1	20	6
				3	20	200	6	<1
				4	6	20	<1	200
	2	1	3	1	20	200	6	<1
				2	<1	6	200	20
				3	6	20	<1	200
				4	200	<1	20	6
		2	4	1	6	20	<1	200
				2	<1	6	200	20
				3	20	200	6	<1
				4	200	<1	20	6

Table VII.4 The experimental design for each batch of turkey poults at six weeks of age, showing the allocation of the illuminance treatments to the compartments.

Age	Batch	Compartment set	Flock	Days	Nominal illuminance in each compartment of the preference chamber			
					Compartment 1	Compartment 2	Compartment 3	Compartment 4
6 wks	1	1	1	1	6	20	<1	200
				2	20	200	6	<1
				3	<1	6	200	20
				4	200	<1	20	6
		2	2	1	20	200	6	<1
				2	200	<1	20	6
				3	<1	6	200	20
				4	6	20	<1	200
	2	1	4	1	6	20	<1	200
				2	200	<1	20	6
				3	20	200	6	<1
				4	<1	6	200	20
		2	3	1	<1	6	200	20
				2	20	200	6	<1
				3	6	20	<1	200
				4	200	<1	20	6

Appendix VIII

Determining the sampling interval for data collection for the preference test experiments.

The following description details how the sampling interval was derived for the preference experiments described in Chapter 5. This followed a modified version of a simple approach suggested by Martin and Bateson (1993).

1. The video tapes of day 3 of testing at two weeks of age for batch 1 (flocks 1 and 2) of the ducklings and batch 2 (flocks 3 and 4) of the turkey poults were selected from the recordings made. From these, an instantaneous scan/ observation (Martin and Bateson, 1993) was made of every bird, recording both its behaviour and location with the compartment set using a scan interval of 5 minutes. Five minutes was the minimum scan interval that could be utilised due to the time-lapse video recordings.

2. These data were summed over the 22 h period (12 birds x 22 h x 6 observations per hour = 3168 data points d^{-1}) to obtain estimates of the total time spent performing each of the behaviours and in each illuminance/compartment.

3. These data were then imported into a Microsoft Excel '97 spreadsheet.

4. Using these data, estimates of the occupancy of the treatments and of time allocations for each behaviour category at intervals of 10, 15 and 20 minutes were made (e.g. for the 10 minute estimate, data at 5, 15, 25, 35 minutes etc, were not included in the sum over the 22 h period, but data for 10, 20, 30, 40 minutes were).

5. The sums of the total time spent in each treatment/compartment and performing the behaviours monitored were then converted into percentages, for each sampling interval.

6. The maximum acceptable discrepancy between the 5 minute sampling and other intervals was specified at 5%.

7. The percentage of discrepancy between the 5 minute sampling and the longer intervals was then calculated.

8. The number of behavioural categories and illuminance treatments/compartments for each sampling interval which satisfied this condition were added up (i.e. those that produced estimates of behaviour time allocations that were ≤ 5% of those derived from 5 minute interval sampling).

9. The results are shown in Tables VIII.1 and VIII.2

Table VIII.1 A summary of sampling period data for occupancy of illuminances/compartments.

Species	**Number of illuminances/compartments for which discrepancy is ≤ 5% for each sampling interval**			
	5 minutes	10 minutes	15 minutes	20 minutes
Ducklings	4	4	3	2
Turkey poults	4	4	3	3

Table VIII.2 A summary of sampling period data for behavioural observations.

Species	**Number of behavioural categories for which discrepancy is ≤ 5% for each sampling interval**			
	5 minutes	10 minutes	15 minutes	20 minutes
Ducklings	9	9	3	3
Turkey poults	12	12	7	5

10. From this assessment a sampling interval of 10 minutes was chosen (shown in red), as it would provide a good approximation to the 5 minute sampling interval, which was the minimum that could be used. The longer sampling intervals would have introduced substantial inaccuracies for many of the behavioural categories.

References:

Martin, P. and Bateson, P. (1993) *Measuring behaviour: an introductory guide, 2nd edition*. Cambridge University Press, Cambridge, UK.

Appendix IX

ANOVA analyses tables for preference test experiments.

The following tables (IX.1, IX.2, IX.3 and IX.4) show the ANOVA analyses tables of the overall occupancy and behavioural data for the preference experiments detailed in Chapter 5. All analyses were performed using GenStat 5 (Release 4.2. Lawes Agricultural Trust, 1989).

Table IX.1 ANOVA table from the analysis of the occupancy data for ducklings from the preference experiment detailed in Chapter 5.

Source of variation	**d.f.**	**s.s**	**m.s**	**v.r.**	**P-value**
Batch stratum	1	5202	5202	1.00	
Batch.age stratum					
Age	1	5202	5202	1.00	0.500
Residual	1	5202	5202		
Batch.age.compartment set stratum					
Flock	1	0	0		
Age.flock	1	0	0		
Residual	2	0	0		
Batch.age.compartment set.test days stratum	24	62424	2601	0.04	
Batch.agew.compartment set.compartment stratum	24	3126364	130265	1.87	
Batch.age.compartment set.test days. compartment stratum					
Light	3	666575	222192	3.20	0.03
Age.light	3	114126	38042	0.55	0.652
Flock.light	3	105774	35258	0.51	0.679
Age.flock.light	3	156836	52279	0.75	0.525
Residual	60	4169745	69496		
Total	127	8417450			

Table IX.2 ANOVA table from the analysis of the occupancy data for turkey poults from the preference experiment detailed in Chapter 5.

Source of variation	d.f.	s.s	m.s	v.r.	P-value
Batch stratum	1	335	335	1.00	
Batch.age stratum					
Age	1	477	477	1.42	0.444
Residual	1	335	335	1.00	
Batch.age.compartment set stratum					
Flock	1	477	477	1.42	0.355
Age.flock	1	477	477	1.42	0.355
Residual	2	670	335		
Batch.age.compartment set.test days stratum	24	3467	144	0.00	
Batch.agew.compartment set.compartment stratum	24	1422516	59271	1.38	
Batch.age.compartment set.test days. compartment stratum					
Light	3	13203736	4401245	102.17	<0.001
Age.light	3	4884435	1628145	37.80	<0.001
Flock.light	3	93397	31132	0.72	0.542
Age.flock.light	3	21783	7261	0.17	0.917
Residual	60	2584537	43076		
Total	127	22216638			

Table IX.3 ANOVA table from the analysis of the behaviour data for ducklings from the preference experiment detailed in Chapter 5.

Source of variation	d.f. (m.v.)	s.s	m.s	v.r.	P-value
Batch stratum	1	0.1864	0.1864	0.43	
Batch.age stratum					
Age	1	8.8936	8.8936	20.52	0.138
Residual	1	0.4334	0.4334	0.05	
Batch.age.compartment set stratum					
Flock	1	10.8130	10.8130	1.21	0.385
Age.flock	1	1.4349	1.4349	0.16	0.727
Residual	2	17.8198	8.9099		
Batch.age.compartment set.test days stratum	24	59.6113	2.4838	0.37	
Batch.agew.compartment set.compartment stratum	24	313.0530	13.0439	1.95	
Batch.age.compartment set.test days. compartment stratum					
Light	3	102.9824	34.3275	5.13	0.003
Age.light	3	5.5186	1.8395	0.27	0.843
Flock.light	3	4.7921	1.5974	0.24	0.869
Age.flock.light	3	31.0729	10.3576	1.55	0.212
Residual	58 (2)	388.3964	6.6965	17.59	
Batch.age.compartment set.compartment.test days.compartment. behaviour stratum					
Behaviour	8	1901.5633	237.6954	624.53	<0.001
Age.behaviour	8	74.9363	9.3670	24.61	<0.001
Flock.behaviour	8	6.5764	0.8221	2.16	0.029
Light.behaviour	24	20.6756	0.8615	2.26	<0.001
Age.flock.behaviour	8	3.9401	0.4925	1.29	0.243
Age.light.behaviour	24	25.0486	1.0437	2.74	<0.001
Flock.light.behaviour	23 (1)	11.1802	0.4861	1.28	0.173
Age.flock.light.behaviour	21 (3)	4.9166	0.2341	0.62	0.910
Residual	740 (156)	281.6422	0.3806		
Total	989 (162)	2050.3832			

Table IX.4 ANOVA table from the analysis of the behaviour data for turkey poults from the preference experiment detailed in Chapter 5.

Source of variation	**d.f.**	**s.s**	**m.s**	**v.r.**	**P-value**
Batch stratum	1	3.1840	3.1840	14.33	
Batch.age stratum					
Age	1	279.2221	279.2221	1256.88	0.018
Residual	1	0.2222	0.2222	0.03	
Batch.age.compartment set stratum					
Flock	1	12.5478	12.5478	1.45	0.351
Age.flock	1	22.4246	22.4246	2.60	0.248
Residual	2	17.2579	8.6290		
Batch.age.compartment set.test days stratum	24	232.5748	9.6906	1.19	
Batch.agew.compartment set.compartment stratum	24	296.5381	12.3558	1.52	
Batch.age.compartment set.test days. compartment stratum					
Light	3	2252.8059	750.9353	92.35	<0.001
Age.light	3	327.3474	109.1158	13.42	<0.001
Flock.light	3	39.8632	13.2877	1.63	0.191
Age.flock.light	3	11.8546	3.9515	0.49	0.693
Residual	60	487.9044	8.1317	11.89	
Batch.age.compartment set.compartment.test days.compartment. behaviour stratum					
Behaviour	11	1780.8328	161.8939	236.66	<0.001
Age.behaviour	11	186.7140	16.9740	24.81	<0.001
Flock.behaviour	11	8.5516	0.7774	1.14	0.328
Light.behaviour	33	247.7344	7.5071	10.97	<0.001
Age.flock.behaviour	11	13.2644	1.2059	1.76	0.056
Age.light.behaviour	33	101.505	3.0785	4.50	<0.001
Flock.light.behaviour	33	22.2589	0.6745	0.99	0.491
Age.flock.light.behaviour	33	14.8155	0.4490	0.66	0.933
Residual	1232	842.8003	0.6841		
Total	1535	7202.3094			

References:

Lawes Agricultural Trust (1989) *Genstat 5 Reference Manual* . Oxford University Press, New York, USA.